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Lifetime and Reliability of a Frequency Converter's Fan

This study is a thesis submitted in partial fulfillment of the requirements for the degree of Master of Science in Technology.

Helsinki, April 30th, 2013

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ABSTRACT OF MASTER'S THESIS

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When an electrical device is used, heat losses are generated. Heat causes several failure mechanisms and accelerates wear of materials shortening the lifetime of the components, and therefore, cooling is needed. A fan is an essential part of the cooling system of a frequency converter. In this thesis, the lifetime and reliability of a frequency converter's cooling fan were examined.

Aim of this work was to advance prognosticating the lifetime of a fan. Different failure mechanisms of a fan were analyzed, and it was discovered that a ball bearing is the part of a fan which most probably fails first. Moreover, in a ball bearing, lubricant deterioration is the main reason for failure. In addition, different methods for evaluating the lifetime of a fan were viewed.

As a practical part of this thesis was implemented a program algorithm, which is to predict the lifetime of a fan based on its real loading. The algorithm uses an equation which calculates the life expectancy of a ball bearing for lubricant deterioration. The calculation algorithm adjusts the life expectancy according to the loading history experinced by the fan. The program is to be used in ACS880-01 frequency converter, manufactured by ABB.

Keywords: lifetime, life expectancy, fan, bearing, cooling, failure, reliability, prognostics, frequency converter

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Sähkölaitetta käytettäessä syntyy lämpöhäviöitä. Lämpö aiheuttaa useita vikaantumismekanismeja ja kiihdyttää materiaalien kulumista, mikä lyhentää komponenttien elinikää. Tämän takia tarvitaan jäähdytys. Taajuusmuuttajassa puhallin on oleellinen osa jäähdytysjärjestelmää. Tässä työssä on tutkittu taajuusmuuttajan jäähdytyspuhaltimen elinikää ja luotettavuutta.

Työn tavoitteena oli kehittää puhaltimen eliniän ennustamista. Työssä tutkittiin puhaltimen eri vikaantumismekanismeja ja saatiin selville, että kuulalaakeri on se puhaltimen osa, joka vikaantuu todennäköisimmin ensimmäisenä. Kuulalaakerin ensisijaiseksi vikaantumismekanismiksi todettiin voitelun heikkeneminen. Työssä tarkasteltiin myös erilaisia menetelmiä arvioida puhaltimen elinikää.

Työn käytännöllisenä osana toteutettiin ohjelma-algoritmi, jonka tarkoitus on ennustaa puhaltimen elinikää sen todellisen kuormituksen perusteella. Algoritmi perustuu yhtälöön, josta saadaan laskettua kuulalaakerille voitelun heikkenemisen rajoittama eliniän odote. Algoritmi sovittaa eliniän odotteen arvon sen mukaan, minkälaisen kuormitushistorian puhallin on kokenut. Ohjelma on suunniteltu käytettäväksi ABB:n valmistamassa ACS880-01–taajuusmuuttajassa.

Avainsanat: elinikä, eliniän odote, puhallin, laakeri, jäähdytys, vikaantuminen, luotettavuus, prognostiikka, taajuusmuuttaja

Preface

This master thesis has been accomplished at ABB in the product management team in Helsinki. First of all I want to thank my supervisor professor Jorma Kyyrä who has given me valuable instructions and constructive feedback during this process. I also wish to thank all the ABB staff members who have helped me in my research, especially Pekka Rantanen, Klaus Kangas, Jorma Manninen, Tomas Melin, Olli Kontu and Jarkko Lalu to name but a few. Vesa Vanhatalo is acknowledged as an instructor and Mika Huuhtanen as an administrative manager.

Moreover, I want to thank my parents Jasmine and Olli for supporting me in my studies; my unofficial cello teacher Petja for his significant help; all the co-musicians in our music institute; the special people with whom I have had privilege to share these moments, especially Heidi, Tanja, Laura-Kaisa, Elise, Mikk, Akari, Anna and Tero and my confidants Lorna and Veera.

Helsinki, April 2013

Anna Muttilainen

"It is said that in some countries trees will grow but will bear no fruit because there is no winter there."

- John Bunyan

Table of Contents

Abbreviations, Terms and Symbols

Abbreviations

AC	Alternating current
ALT	Accelerated life test
BJT	Bipolar junction transistor
BLDC	Brushless direct current
BPFI	Ball pass frequency, inner race
BPFO	Ball pass frequency, outer race
BSF	Ball spin frequency
DC	Direct current
DWT	Discrete wavelet transform
ESR	Equivalent series resistance
FTF	Fundamental train frequency
IGBT	Insulated gate bipolar transistor
IP	Ingress protection
MTTF	Mean time to failure
PWM	Pulse-width modulation
UL	Underwriters Laboratories
VSI	Voltage source inverter

Terms and Symbols

AF	Acceleration factor	
a	Mean diameter of rolling elements	[mm]
a_1, a_2, a_3	Adjustment coefficient	
α	Scale parameter	
b	Pitch diameter of a bearing	[mm]
β	Shape parameter	
C_r	Load rating	[N]
C_t	Temperature adjusted load rating	[N]

D	Outer diameter of a bearing	[mm]
d	Inner diameter of a bearing	[mm]
E_a	Activation energy	[eV]
F	Cumulative density function of Weibull distribution	
f_r	Rotation speed of a bearing shaft	[Hz]
f_{rC}	Fundamental train frequency	[Hz]
f_{rI}	Ball pass frequency, inner race	[Hz]
f_{rO}	Ball pass frequency, outer race	[Hz]
f_{rR}	Ball spin frequency	[Hz]
f_t	Temperature coefficient	
φ	Contact angle	[°]
Γ	Gamma function	
k	Boltzmann's constant, slope	[eV/K], [%/h]
L	Life expectancy	[h]
n	Rotation speed, number of fans, number of rolling elements	[rpm] -
N_{lim}	Limiting speed with grease lubrication	[rpm]
P_r	Equivalent radial load rating	[N]
T	Temperature	[°C]
t	Time	[s], [h]
y	Amount of accumulated percents	[%]

1 Introduction

Electrical devices belong indivisibly to today's society. When an electrical device is used, heat losses are generated, and therefore, efficiency and energy conservation have become major subjects in the development of electrical technologies. It is noteworthy that wasted energy is not the only issue regarding the losses of electrical devices. Heat causes several failure mechanisms and accelerates the wear of materials making the lifetime of components shorter. Consequently, a cooling system is needed to enable proper performance of a device.

A frequency converter improves process efficiency and reduces energy consumption, and hence, it is a significant contributor to energy conservation. In this thesis we examine the lifetime and reliability of a frequency converter's cooling fan. Reliability can be defined as a device's or a component's ability to perform intended function for a certain duration at certain circumstances. Reliability requirements of frequency converters have increased exceedingly during past years, and reliability of the fan is a significant factor in reliability of the frequency converter. In this work we aim to promote a prognostic approach, which means evaluating the lifetime and reliability of a device under its actual operating conditions. More specifically, we aim to advance predicting the lifetime of a frequency converter's cooling fan based on its loading.

The core of this work can be stated as follows:

When a frequency converter is in use, heat losses are generated, and therefore, a cooling system is needed. A fan is an essential part of the cooling system of a frequency converter, and the lifetime of a fan is limited. As we will see later on, in a fan, a ball bearing is the weakest component, i.e. the component which has the highest probability to fail first. Moreover, in a ball bearing, lubricant deterioration is the main reason for failure. (Fig. 1)

Since the lifetime of a fan is shorter than the lifetime of some other parts of a frequency converter, the fan has to be replaced after a period of time. The practical part of this work is implementing a program which is to predict the lifetime of a fan. Purpose of the program is to provide information on how long a fan is expected to function based on the real loading experienced by the fan. Since a ball bearing is the part of a fan which most probably fails first, and lubricant deterioration is the main failure reason of it, the program is supposed to calculate the life expectancy of a ball bearing limited by this failure mechanism. The program is to be used in ACS880-01 frequency converter, manufactured by ABB.

Need for a program which predicts the lifetime of a fan based on its real loading is obvious. At the moment, the control of a fan's lifetime in the frequency converter's software is performed by a simple counter. The counter starts to run at the beginning of the fan's usage, and when it reaches a user-defined time limit, the software gives a warning to the user to replace the fan.

This thesis is organized as follows. In Chapter 2 we aim to analyze the three main elements of this work: frequency converter, fan and bearing. Chapter 3 is for failure and reliability analysis. It includes discussion of failure classification, reliability metrics and common stresses on electronic products and their effects. Moreover, failures of a fan and evaluation methods for the lifetime and reliability of a fan are analyzed. In Chapter 4 we introduce the program implemented by the author. We present the calculation method and the structure of the program and assess its limitations. In Chapter 5 we make conclusions of the work and put forward some suggestions for further study.

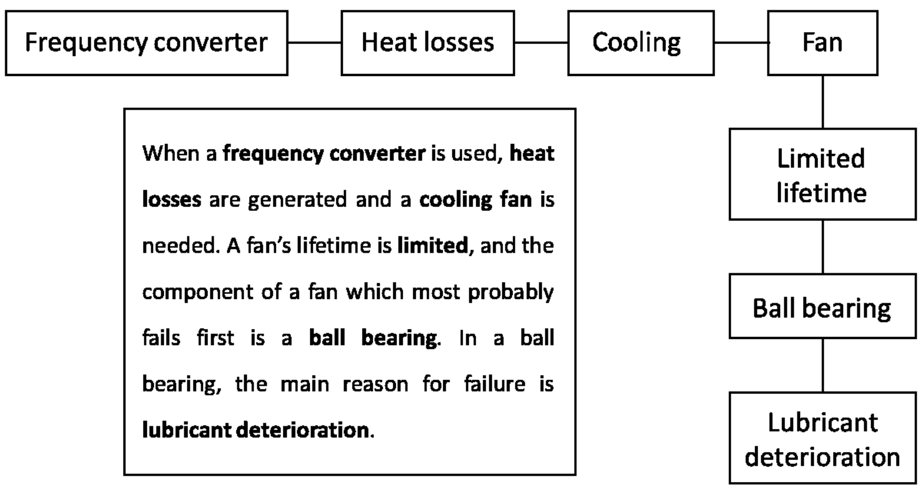


Fig. 1: The composition of this research

2 Frequency converter, fan and bearing

In this Chapter we aim to analyze the three main elements of this work: frequency converter, fan and bearing. First, we discuss a frequency converter's operation principle and its losses. Second, we consider cooling methods of electrical devices, a fan as the most important one, and introduce the cooling system of the studied frequency converter, ACS880-01. Finally, we examine bearings and tribological issues, specifically friction, wear and lubrication.

2.1 Frequency converter

Purpose of a frequency converter is to convert an alternating voltage of one frequency to an alternating voltage of another frequency. A frequency converter consists of three parts: an AC-DC converter, a DC link and a DC-AC converter. Most widely used three-phase frequency converter topology is constructed from a six-pulse diode bridge rectifier and a two-level pulse-width modulated (PWM) voltage source inverter (VSI). In this topology the diode bridge rectifier provides the AC-DC conversion and the VSI inverter produces the AC output from the DC voltage stored in the capacitors of the DC link. The block diagram of such a frequency converter is shown in Fig. 2.

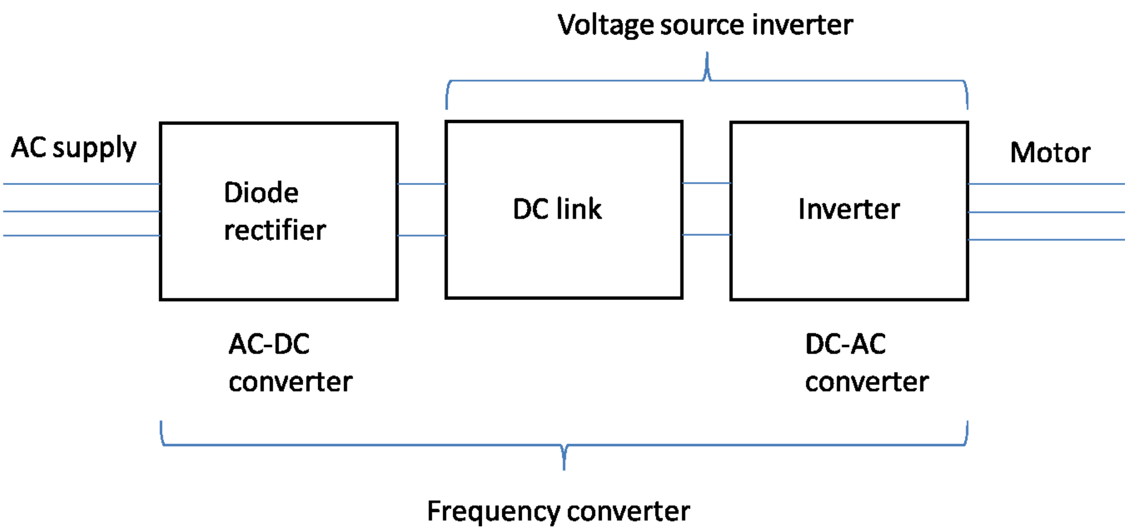


Fig. 2 The block diagram of a frequency converter

Since a frequency converter mediates between a power system and a motor, it has to fulfill certain requirements. The frequency of the output voltage has to be controllable according to the needs of the motor. Moreover, the amplitude of the output voltage has to be controllable as well and even independently from the frequency (Kyyrä 2010, p. 155, Mohan 2003, p. 418). These quantities are controlled by the switches of the converter. The PWM inverter controls both the amplitude and the frequency of the output voltage, and therefore, an uncontrollable rectifier, i.e. a diode rectifier, can be used at the input. In the PWM-VSI inverter, several components can be used as switches. In the beginning of the usage of the PWM-VSI inverters, thyristors were used in this purpose; later BJTs (bipolar junction transistor) and nowadays most widely IGBTs (insulated gate bipolar transistor) (Blaabjerg 1995, p. 434). A more detailed illustration of a frequency converter is shown in Fig. 3.

An often used PWM method to control the switches of the inverter is sinusoidal-triangular wave comparison. In this method the amplitude of the output voltage is determined by the amplitude of the sinusoidal wave and the frequency by the frequency of the sinusoidal wave.

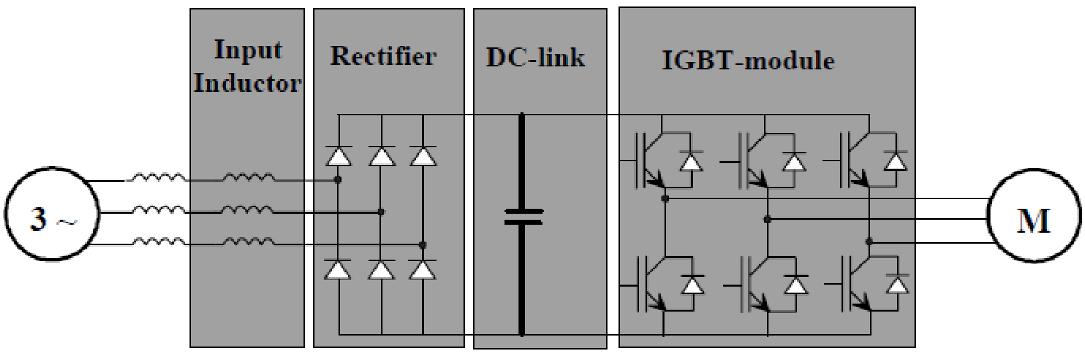


Fig. 3 The main circuit of a frequency converter (Aarniovuori et. al 2007)

2.2 Losses in a frequency converter

A frequency converter's losses consist of input inductor losses, diode rectifier losses, intermediate circuit losses, PWM-VSI inverter (IGBT module) losses and extra losses i.e. losses in the auxiliary devices. The analysis below is based on Sousa et al. (1992) and Aarniovuori et al. (2007).

Input inductor losses

The input inductor losses are generated in the inductors' cores and windings. The core losses occur due to hysteresis and eddy currents. The losses of the windings depend on the inductor line current and the equivalent series resistance, ESR.

Diode rectifier losses

In a diode rectifier, the most considerable losses are the conduction losses. The blocking state losses and the switching losses are negligible. The conduction losses can be calculated from the diode average current, the forward voltage drop and the on-state resistance.

Intermediate circuit losses

The DC link current comprises a DC component, harmonics generated by the diode bridge rectifier and switching harmonics generated by the IGBT inverter. The most remarkable losses in the DC link are the losses of the capacitor bank and of the discharge resistors. The losses of the capacitor bank consist of dielectric losses and ohmic losses. The capacitor losses can be represented by the equivalent series resistance, ESR.

PWM-VSI Inverter (IGBT module) losses

In the IGBT module, the switching losses and the conduction losses are considerable. These losses consist of the switching and the conduction losses of each IGBT and its antiparallel feedback diode.

Extra losses

Extra losses are the losses in the auxiliary devices, including the cooling fan and the control system power consumption.

2.3 Cooling of electrical devices

Due to the heat losses generated in all electrical devices, cooling is needed. Cooling methods can be classified according to the used medium into air cooling and liquid cooling. Air cooling is further divided into natural and forced air cooling.

2.3.1 Air cooling

Advantages of air cooling are simplicity and excellent availability of the cooling medium (Tong 2011, p. 374). Main problems of air cooling are humidity and dust of the surrounding air and especially corrosive substances that may exist in an industrial environment. These disadvantages can be reduced by filtering the incoming cooling air and maintaining positive pressure inside the device. (Niiranen 2007, p. 153)

Natural air cooling is based on natural way of warm air to flow up. The cooling air absorbs heat generated by the device in use, and because the heated air is lighter than the cooler air, it rises up and is replaced by the cooler air from below. This cycle repeats itself. Natural convection is sufficient for cooling circuit boards that dissipate up to about 5 W of power. Therefore natural air cooling is suitable especially for small electronic products with low heat output. In many consumer electronic devices, natural cooling is implemented by equipping the case with a proper amount of vents for the cool air to enter and the hot air to leave the case freely. (Tong 2011, p. 374)

When natural air convection is not sufficient, airflow is generated by an external device such as a fan, a blower or a pump. This method is called forced air convection. A fan is widely used equipment for this purpose in electronic systems as in the frequency converter studied here. With forced air cooling, hot surfaces are typically equipped with extended surfaces, such as fins in heat sinks. (Tong 2011, p. 375)

2.3.2 Liquid cooling

Electrical devices can be cooled with the help of liquids as well. The principle is that the heat generated by the device in use is transferred to the liquid, and furthermore, to the atmosphere (Chitode 2009, p. 1-126). Usually water or oil is used as a medium. Azar et al. (2008, p. 67) point out the term liquid cooling is somewhat misleading. When liquid cooling is used, air is anyway the final coolant and the liquid acts as a heat exchanger and not as a coolant. Advantages of using water as the medium in liquid cooling are its heat transfer capacity and low price. However, disadvantages are electrolytic corrosion due to impurities of water and possible freezing. (Niiranen 2007, p. 153)

2.3.3 Heat sink

A heat sink is a cooling device which absorbs or dissipates heat from surroundings. It uses extended surfaces such as fins and spines for transferring the heat. Performance of a heat sink depends on thermal conductivity of the fins, the surface area of fins and the heat transfer coefficient. (Lee 2010, p. 34)

2.4 Fan

In this passage we will introduce the structure of a fan and discuss main requirements a fan has to fulfill, i.e. main considerations in selection of a fan.

2.4.1 Structure

The core components of a fan are rotating blades and an electric motor (Fig. 4). The electric motor consists of a stator located in a fan housing and a rotor, and the blades are attached on the rotor. The structure disassembled into two parts is shown in Fig. 5. When the fan is in use, a permanent magnet in the rotor interacts with the electromagnetic force generated by the stator making the rotor to rotate.

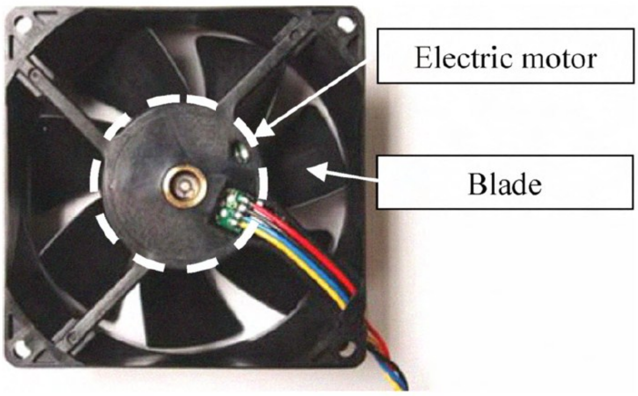


Fig. 4: The structure of a fan (Oh et al. 2010)

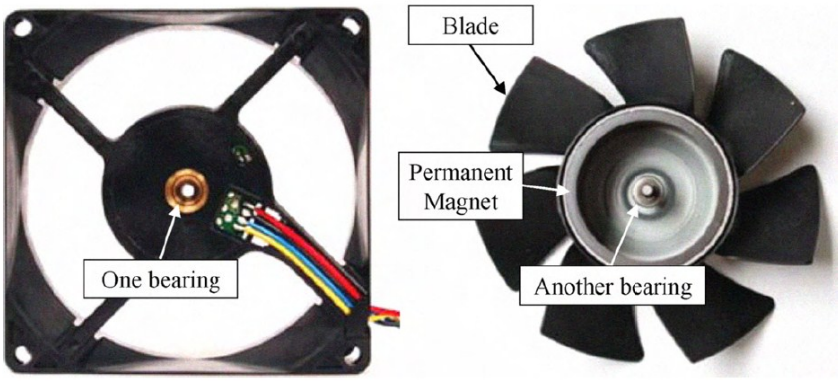


Fig. 5: a) A stator in a fan housing b) a rotor with blades (Oh et al. 2010)

A brushless direct current (BLDC) drive and a stator mounted on the fan housing are shown in Fig. 6. The BLDC drive is composed of transistors, resistors, capacitors and ICs.

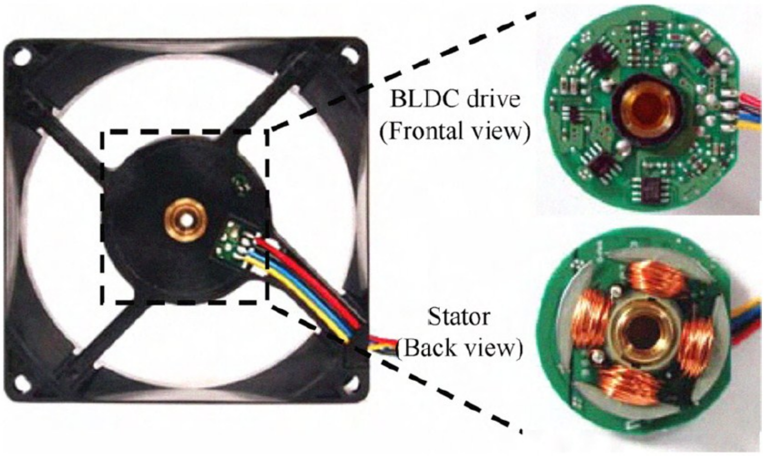


Fig. 6: A BLDC drive and a stator (Oh et al. 2010)

2.4.2 Primary considerations in selection of the fan

There are two primary considerations in selection of a fan. The first one, the force resisting the flow of the air in a device is called ventilating resistance (also known as system impedance or channel resistance). This force is generated due to the layout of the parts and the shape of the airflow inside the device. Fig. 7 illustrates the magnitude of the ventilating resistance. When the air can move straight ahead within a free space, the resistance is small. When the air has to go through narrow channels or when the direction of airflow changes, the resistance increases. (Servo 2009, p. G-6)

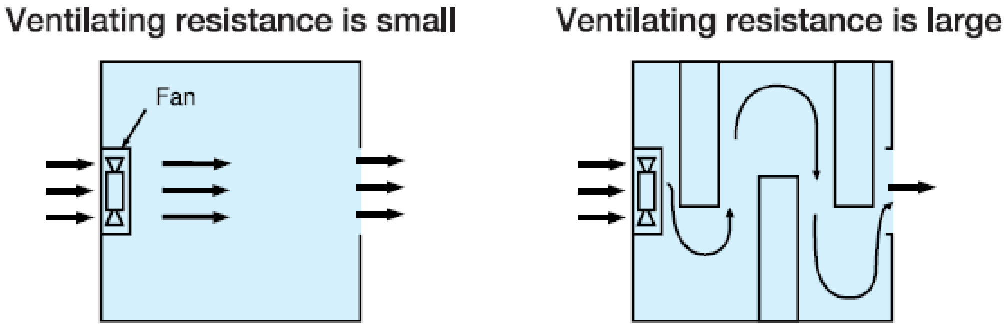


Fig. 7: Ventilating resistance (Servo 2009, p. G-6)

The second primary consideration is sufficient airflow. Required airflow depends on the heat generation rate (i.e. the ventilating heat release) (W), temperature and temperature rise of the air. Fig. 8 shows the dependence between these variables when the initial temperature of the air is 25 °C. (Servo 2009, p. G-6)

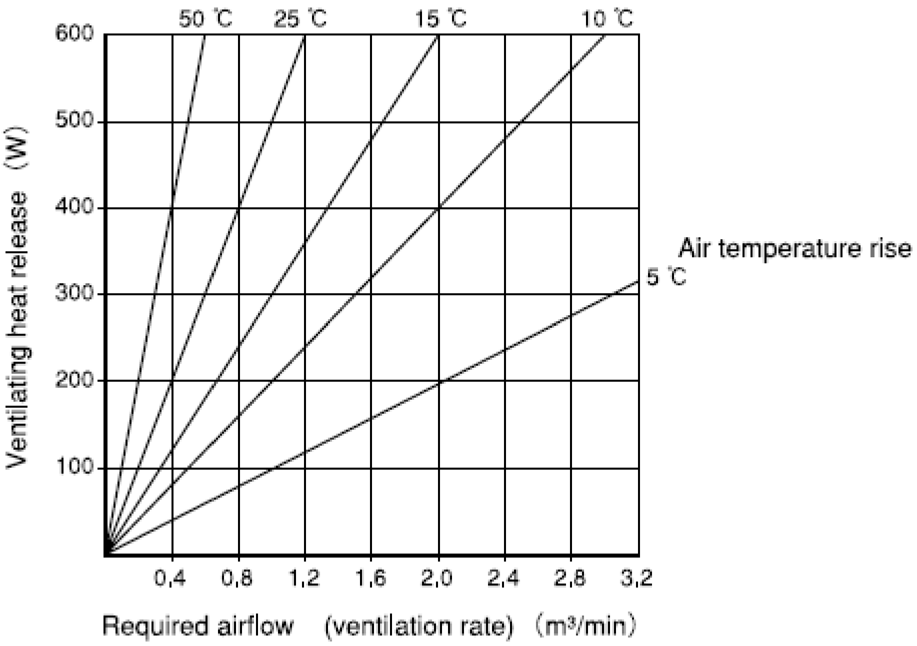
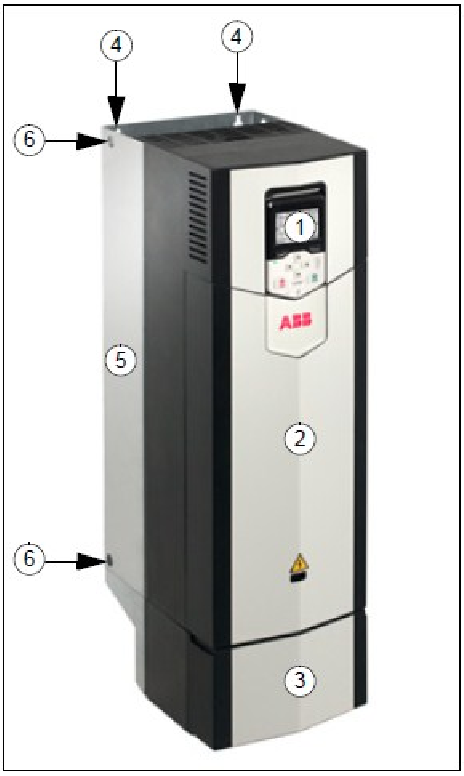


Fig. 8: Required airflow of a fan vs. heat generation rate (W) and temperature rise of the air (°C) when initial temperature of the air is 25 °C (Servo 2009, p. G-6)

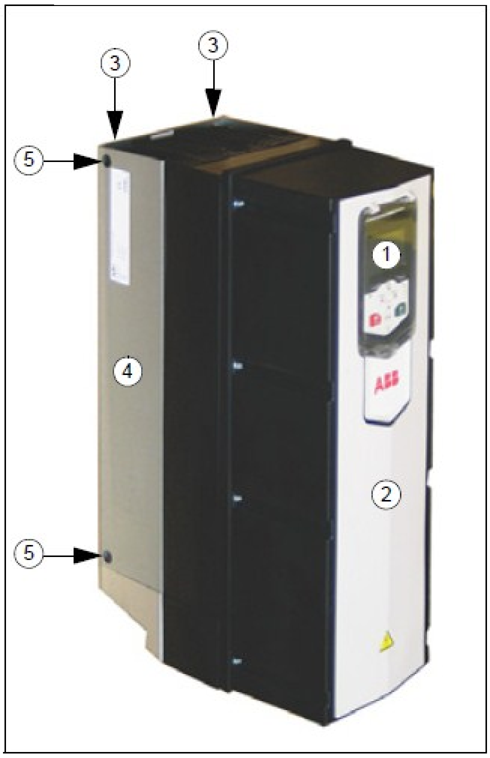
2.5 Structure of ACS880-01 and location of the cooling components

ACS880-01 is a low voltage frequency converter for industrial purposes. Main circuit of ACS880-01 is implemented as introduced in Chapter 2.1 and is accompanied with other components such as cooling devices. ACS880-01 exists in nine different frame sizes: from R1 (smallest) to R9 (largest). Each frame size exists in two different types: IP21, UL Type 1 and IP55, UL Type 12 (IP: ingress protection, UL: Underwriters Laboratories). The compositions of these two types are shown in Fig. 9 and Fig. 10. According to the hardware manual (ABB 2012, p. 145), the efficiency of the frequency converter is about 98 %. Fig. 11 illustrates the cooling of ACS880-01. The arrows scratched out in the figure show the ways air should not flow: recirculation of the cooling air should not occur either inside or outside the cabinet.



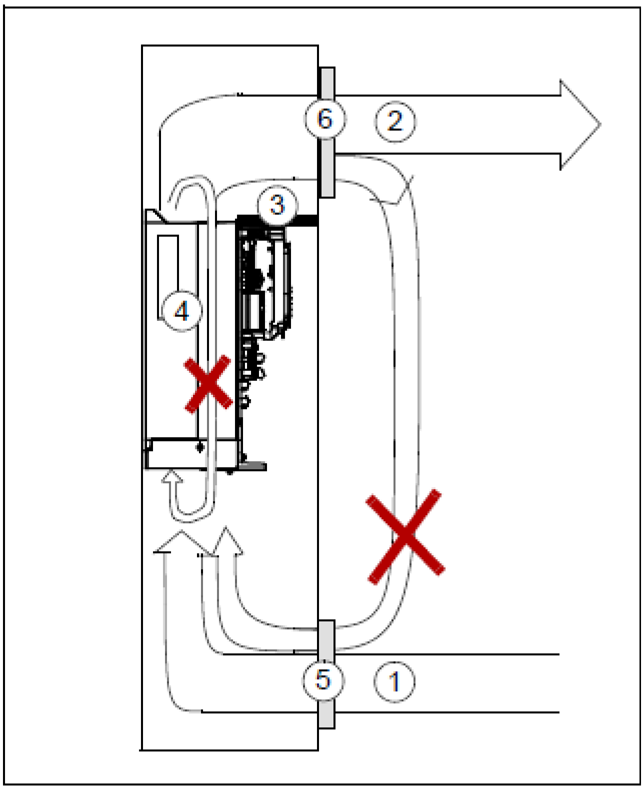
1	Control panel
2	Front cover
3	Cable entry box
4	Four fastening points at the back of the unit
5	Heat sink
6	Lifting holes

Fig. 9: Frequency converter ACS8800-1, IP21 UL Type 1, (view of frame R5) (ABB 2012, p. 29)



1	Control panel behind the control panel cover
2	Front cover
3	Four fastening points at the back of the unit
4	Heat sink
5	Lifting holes

Fig. 10: Frequency converter ACS8800-1, IP55 UL Type 12, (view of frame R4) (ABB 2012, p. 30)



1	Main air flow in
2	Main air flow out
3	Air baffle plate
4	Drive
5	Air inlet filter
6	Air outlet filter

Fig. 11: Cooling of ACS880-01. The arrows scratched out show the ways air should not flow: recirculation of cooling air should not occur either inside or outside the cabinet (ABB 2012, p. 49)

Fig. 12 and Fig. 13 present the main fans of different frame sizes of ACS880-01. In the devices of frame sizes from R1 to R5, the main fan is located at the top of the device whereas in frames from R6 to R9, it is located at the bottom of the device.

Fig. 12: The main cooling fan of ACS880-01, frame sizes R1-R3 (ABB 2012, p. 116)

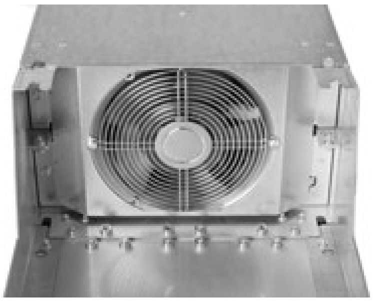


Fig. 13: The main cooling fan of ACS880-01, frame sizes R6-R8 (view from bottom) (ABB 2012, p. 120)

2.6 Bearing

Bearings are divided into two groups: sliding contact (plain) bearings and rolling contact (antifriction) bearings (Fig. 14). We will pay more attention on the latter group since the bearings of the fans used in the studied frequency converter represent it. Rolling contact bearings have several advantages in comparison with sliding contact bearings (NSK 2011, p. A 7, Orlov 1977, p. 257): more accurate centring of the shaft, low coefficient of friction, weak dependence on the coefficient of friction on operating conditions, low resisting moments during starting periods, small axial dimensions, ability to operate with a small oil feed, ability to operate within a wide temperature range and ability to operate in high vacuum. However, rolling contact bearings have also some disadvantages: large radial dimensions and weight, high cost, uneven operation, incapability of dampening load variations, noise in operation, complicated installation and assembly, high sensitivity to installation inaccuracies and incapability of being split in the meridional plane.

Operation of **sliding contact bearings** is based on a sliding action between surfaces in contact. A clearance fit between the inside diameter of the bearing and the shaft is critical to enable proper operation. Sliding contact bearings are most commonly made from bronze and phosphor bronze. (Madsen 2004, p. 532-533)

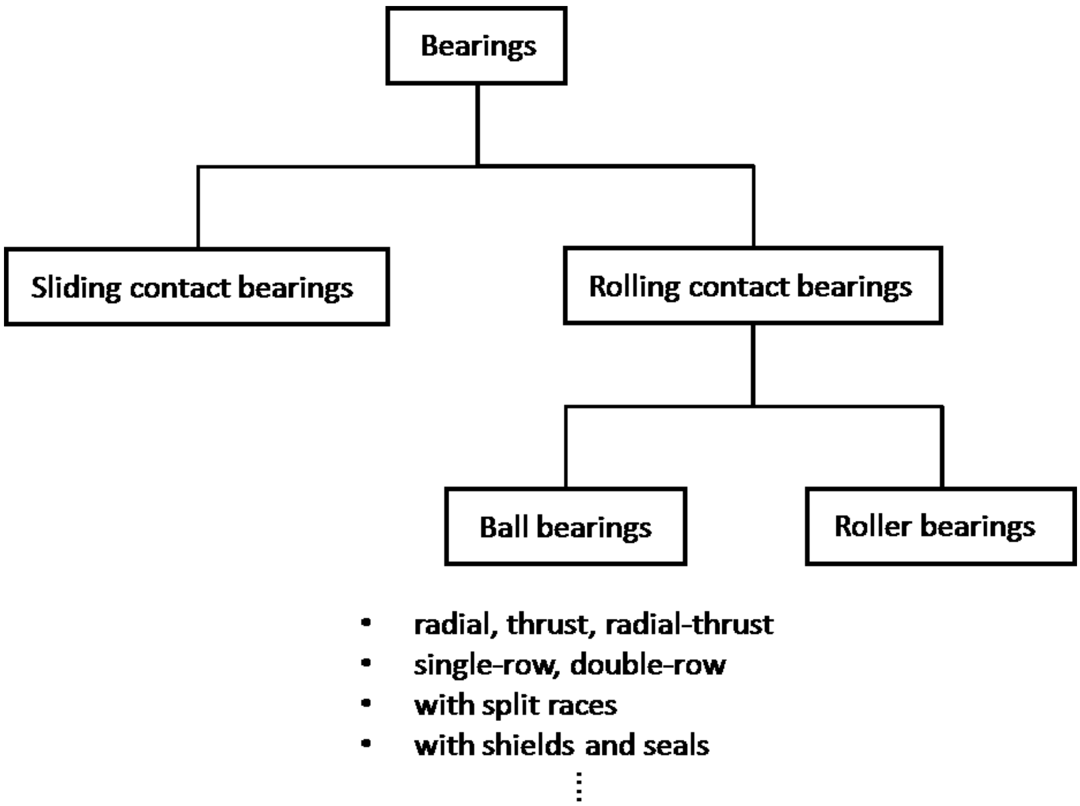


Fig. 14: Classification of bearings

Rolling contact bearings are classified into two major categories: ball bearings and roller bearings (Fig. 14). Generally ball bearings have higher speed and lower load-carrying capacity. Ball bearings are used in the devices we are examining. These two types are shown in Fig. 15.

Fig. 15: The types of rolling contact bearings: a) ball bearing b) roller bearing (NSK 2013)

Fig. 16: The main elements of ball bearings: a) outer ring b) inner ring c) rolling elements d) cage (NSK 2013)

Ball bearings are composed of four main elements which are shown in Fig. 16.

- a) Outer ring: the large ring of the outer race
- b) Inner ring: the small ring of the inner race
- c) Rolling elements: a set of balls or placed between the outer and inner rings
- d) Cage: keeps the balls apart and aligned

Load carrying capacity of a bearing is generally expressed by basic static load rating and basic dynamic load rating. Basic static load rating is defined as the static load which causes at the contact area between the rolling element and the raceway surface certain contact stress, i.e. a permanent deformation of 0,0001 times the diameter of the rolling element. Basic dynamic load rating is defined as the constant load which the bearing can carry at normal conditions of one million revolutions. Load carrying capacity of a bearing used in any application is determined by dimensions of the bearing. Therefore, the dimensions influence also the lifetime and reliability of the bearing, as we will see later on. Dimensions are defined in Fig. 17. (Sharma 2005, p. 594, NSK 2011, p. A 32)

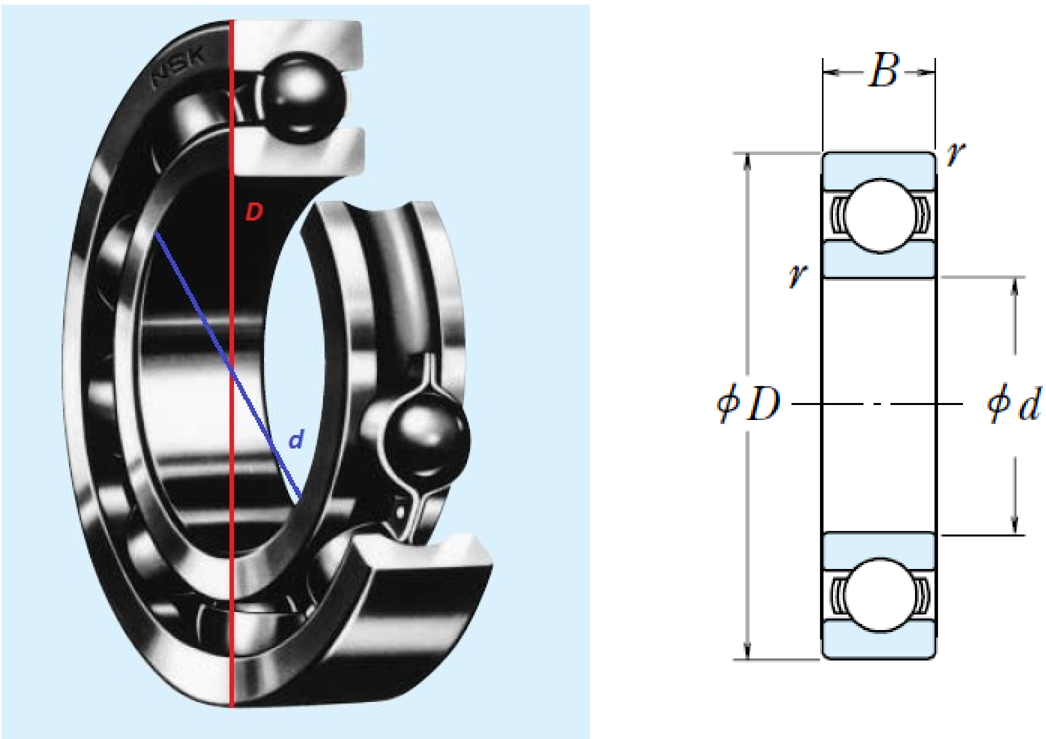


Fig. 17: a) Inner and outer diameters and b) a cross-section of a ball bearing (NSK 2011, p. B 4-8)

There are different types of both ball and roller bearings in respect of their structure, load-carrying capacity etc. Here we list main classification properties of ball bearings:

- Radial (rotational), thrust (linear, axial) and radial-thrust bearings

Rotational bearings are used for radial loads and linear bearings for thrust loads. Radial load means a load which is distributed around the shaft whereas thrust (axial) loads are lateral (Madsen 2004, p. 532). Radial-thrust bearings can carry radial and axial loads simultaneously (Orlov 1977, p. 260).

- Single-row and double-row bearings

Both radial and thrust bearings can exist as single-row or double-row bearings. Double-row radial ball bearings have two rows of rolling elements next to each other and they have increased load-carrying capacity compared to single-row radial ball bearings. Single-row thrust ball bearings are used for unidirectional axial loads, whereas double-row thrust ball bearings are intended to carry bidirectional axial loads. (Orlov 1977, p. 258-262)

- Bearings with split races

Splitting the races enables increasing the number of balls and deepening the raceways. Bearings with split races can carry heavy axial and radial-axial loads. (Orlov 1977, p. 263)

- Bearings with seals and shields

Ball bearings can be equipped with one-sided or two-sided shields. Shields are made of metal and they protect the bearings against appearance of dirt. A sealed bearing possesses seals made of rubber, felt or plastic on the outer and inner rings. Sealed bearings demand no or little maintenance in service. (Orlov 1977, p. 264, Madsen 2004, p. 533)

- Angular contact ball bearings

In an angular contact ball bearing, the rolling element meets the inner and the outer ring raceways at a contact angle. This means that raceways in the inner and the outer ring are displaced in respect of each other in the direction of the bearing axis. It can take radial and axial loads and combinations. It can be either single-row or double-row. (NSK 2011, p. A 10, NSK 2013)

2.7 Tribological issues

Tribology is defined as "the science and technology of interacting surfaces in relative motion and of related subjects and practices" (Sahoo 2005, p. 1). Generally, tribology deals with lubrication, friction and wear and, hence, it is an important science when examining bearings. As mentioned, ball bearings are used in the devices we are examining here, and therefore, we will concentrate most on tribological issues that are meaningful regarding ball bearings and rolling motion.

2.7.1 Friction and rolling motion

Friction is defined as a force of resistance to a relative motion of two solid particles. The ratio of friction force to the normal load is called coefficient of friction. Friction can be classified into sliding friction, which takes place in a sliding motion and rolling friction, which takes place in a rolling motion, respectively. Rolling friction is much lower than sliding friction: the coefficient of rolling friction for hard materials varies from $5 \cdot 10^{-3}$ to 10^{-5}, whereas the coefficient of sliding friction is from 0,1 to 1 or ever larger. (Sahoo 2005, p. 61)

Relative motion occurring during rolling motion is a combination of rolling, sliding and spin. Rolling is the relative angular velocity between the bodies in contact in respect of an axis in the tangent plane of contact. Sliding is the relative linear velocity between the two surfaces at the contact point. Spin is the relative angular velocity between the bodies in respect of the common normal through the contact point. (Sahoo 2005, p. 61)

2.7.2 Lubrication

The main purpose of lubrication in rolling contact bearings is to prevent direct metallic contact between the bearing rings, the rolling elements and the cage and, hence, to reduce friction and wear in the contact areas (NSK 2011, p. A 105). Lubrication can also have other purposes such as cooling, preventing corrosion, protection from contaminants and minimizing maintenance (Khonsari 2008, p. 469). When there is a lubricating film between the two surfaces in contact, commonly known friction laws (so called dry friction laws) are not applicable, because there is no direct solid-solid contact.

In this case, friction is the force of resistance to a relative motion between *the lubricant* and the surfaces and is called film friction, fluid friction or viscous friction (Phakatkar 2009, p. 1.10).

Lubricants can be classified into four categories: oils, greases, solids and gases. **Lubricating oils** include natural organics like animal fat, whale oil, shark oil, mineral oils, vegetable oils etc. Mineral oils are the most commonly used lubricants. Synthetic organics, such as synthetic hydrocarbons, diesters, chlorofluorocarbon etc. belong to the group of lubricating oils as well. **Lubricating greases** are oils that are thickened with solids into semi-fluid state. The characteristics of a grease are determined by the thickener. Greases ordinarily consist of fluid (85-90 %), such as mineral oil or polyglycol; fatty materials (3-15 %); thickeners (1-4 %) and a small amount of additives and modifiers. The temperature at which the grease melts under certain operating conditions is called drop point. If the grease is used at a temperature higher than the drop point, it loses its advantages it has compared to oil. **Solid lubricants** were developed to offer lubrication which would separate completely two surfaces in sliding motion, even under a high load. A solid lubricant is a thin film which consists of a single solid or combination of solids. Principle of using **gases** as lubricants in certain bearings is similar to that of using oils. Bearings using air as a lubricant are called aerodynamic or aerostatic bearings. (Phakatkar 2009, p. 1.16-1.19)

In rolling contact bearings, both oils and greases can be used as lubricants but grease is the most commonly used. Using grease as lubricant enables simpler housing designs, less maintenance, less difficulty with leakage and generally easier sealing against dirt and moisture (Khonsari 2008, p. 478, Sahoo 2005, p. 257). However, oil provides lubrication superior to grease in several ways: it carries heat away more effectively, enables higher operating speeds and loads and protects better against contaminants such as dirt and water (Khonsari 2008, p. 478).

2.7.3 Wear

Wear is defined as removal of material from one or both surfaces in relative motion. Wear occurs by a mechanical or a chemical process or by a combination of those and is accelerated by a thermal process. Wear mechanisms are usually classified into four main forms: adhesive, abrasive, fatigue and corrosive wear. (Sahoo 2005, p. 72)

Adhesive wear occurs in a sliding contact of two nominally flat solids. As a result of sliding motion some fragments detach from one surface and either attach to the other surface or form loose wear particles. (Sahoo 2005, p. 73, Sundquist 1986, p. 146)

Abrasive wear means damaging process of a surface caused by a harder material. Asperities of the harder surface press against the softer surface which causes plastic flow of the softer surface around the asperities. (Phakatkar 2009, p. 2.32)

Fatigue wear may take place in surfaces in both rolling and sliding contacts. Repeated loading and unloading cycles result in surface cracks, which finally lead to formation of large fragments from the surface. (Sahoo 2005, p. 83)

Corrosive wear occurs as a result of interaction between environment and mating surfaces. In the corrosive wear process rubbing of the surfaces takes place in a corrosive environment, and consequently, a chemical surface reaction occurs leaving the reaction product on one or both surfaces. Repetition of this process results in corrosive failure of the mating surfaces. (Phakatkar 2009, p. 2.35)

Adhesive and abrasive wear occur in a direct solid-solid contact. Therefore, as long as there is a lubricating film between the solid moving surfaces in a ball bearing, visible adhesive or abrasive wear do not occur. Nevertheless, lubrication does not completely prevent fatigue failure. In rolling motion, surfaces of the ball bearing experience large stresses transmitted through the lubricating film, and when the stress amplitude exceeds the fatigue limit of the bearing material, fatigue failure occurs. (Sahoo 2005, p. 83-84)

3 Failure and reliability analysis

In this Chapter we are going to examine failure and reliability issues. First, we will discuss ways to classify failures in electrical devices and introduce some widely used reliability metrics. Afterward we will present common stresses on electronic products and their effects. Moreover, we will treat issues regarding failures of a fan, including fan failure classifications, criteria and modes and mechanisms. Finally, we are going to analyze different methods for evaluating the lifetime and reliability of a fan. Among those methods, we introduce the one we have chosen to use in the program implemented as a practical part of this work, presented in the next Chapter. In the program, we need to have a method which can be used in the studied application, ACS880-01 frequency converter, under its normal operating conditions. This sets some limits for the method: the method cannot be based on quantities that are not measured from the device or special conditions.

3.1 Failure classification

Electronic failures can be classified according to when, how and why they occur. Most often they are classified in respect of the '**when**' question, which means that failures are divided into early-life, midlife and wear-out failures. This division can be illustrated with a bathtub curve, shown in Fig. 18. It is called bathtub curve since the curve representing failure rate in respect of time, has a shape of a bathtub. Early-life failures (infant mortalities) occur due to manufacturing or assembly process defects. During this period the failure rate is high since all the weak products with macroscopic manufacturing defects fail. During the "useful life" (midlife) period the failure rate is relatively constant as a result of randomly occurring failures. Those random failures occur mostly due to external circumstances. Wear-out failures appear as a result of lengthy service under operational or environmental stresses. They will finally occur in every item which is in service long enough. (Martin 1999, p. 1.1-1.2, Ohring 1998, p. 30)

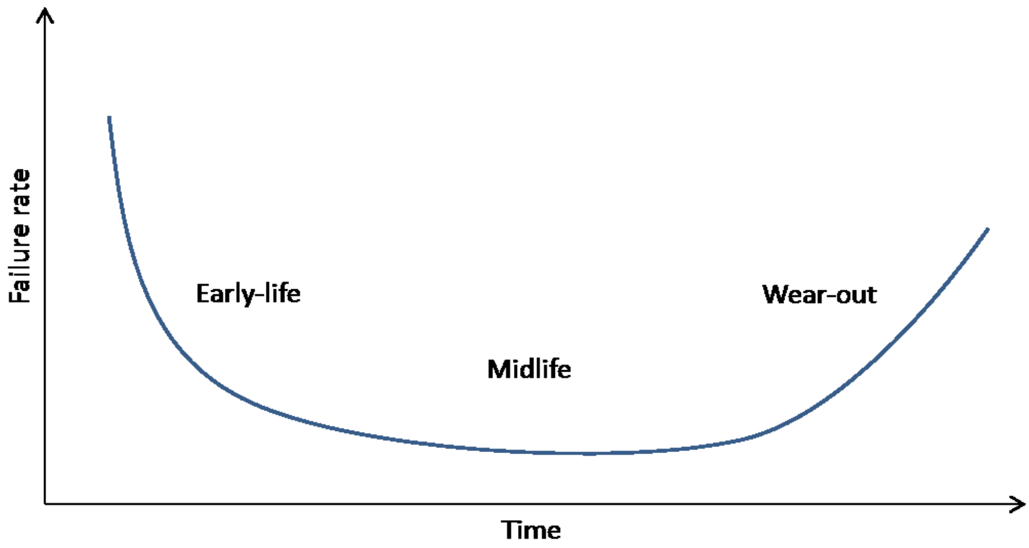


Fig. 18: A bathtub curve

When classifying failures in respect of the '**how**' question, failures are divided according to whether they are gradual or sudden and catastrophic. Gradual failures occur little by little, like tires wear, whereas sudden and catastrophic occur in a moment, such as a light bulb burns out. Finally, regarding the '**why**' question failures can be preordained or random. Preordained failures occur due to an internal mechanism which makes an item to fail deterministically, whereas in random failures there is no such a mechanism. Table 1 shows the connections between these divisions. We can see that early-life failures can represent all the four 'why' and 'how' divisions, and therefore, they are difficult to deal with. Wear-out failures can be gradual or sudden but not random. (Ohring 1998, p. 30-31)

Table 1: Divisions of failures

		When		
		Early-life	Midlife	Wear-out
Why	Preordained	X		X
	Random	X	X	
How	Gradual	X		X
	Sudden and catastrophic	X	X	X

3.2 Reliability metrics

Reliability of electronic products is often represented by life expectancy, and different metrics can be used for this purpose. Mean time to failure, median time to failure and rating life are widely used metrics. If n is the number of products that fail in service after successively longer times t_1, t_2, …, t_4, mean time to failure (*MTTF*) is defined as follows:

$$MTTF = \frac{t_1 + t_2 + \cdots + t_n}{n} \tag{3.1}$$

In contrast, median time to failure L_{50} is defined to occur when 50 % of the products in a sample have failed, i.e. a half of the products fail before and a half after that time. Similarly, rating life L_{10} is the time which 90 % of the products exceed or achieve before they fail.

3.3 Common stresses on electronic products and their effects

In this passage we introduce common stresses electronic products face during their life and effects of those stresses. Analysis is based on Yang (2007, p. 246-252).

3.3.1 Constant temperature

High temperature can bring on various failure mechanisms, such as oxidation, electromigration, creep and interdiffusion. Oxidation occurs when a material is in contact with oxygen. Chemical reaction between the material and oxygen causes formation of oxide compound, and high temperature accelerates that process by providing energy for the chemical reaction. Furthermore, oxidation can result in various failure mechanisms and failure modes, for example, oxidation causes corrosion of metals which can end in fracture of a structure.

Electromigration occurs when an electrical current flows through a metal: electrons exchange momentum with metal atoms which leads to mass transfer. High temperature accelerates the process. The mass transfer causes vacancies and interstitials. Vacancies produce voids and microcracks which may result in, for instance, open circuit. Interstitials may result in short circuit.

High temperature combined with a mechanical stress causes creep process. Creep is a gradual plastic deformation which results in elongation of the component. Creep leads to a component failure due to loss of elastic strength or finally due to fracture.

Interdiffusion occurs when two different bulk materials are in contact at a surface and molecules or atoms of one material move into the other and vice versa. High temperature increases exceedingly the interdiffusion rate. Interdiffusion can result in various failure modes, for instance, increased electrical resistance and fracture.

3.3.2 Thermal cycling

Thermal cycling means applying high and low temperatures repeatedly over time. It is a stress that many products face in the field. Fatigue is the most common failure mechanism that occurs as a result of thermal cycling. When thermal cycling is applied to a product, two different materials connected to each other inside the product expand and contract repeatedly. Since the thermal coefficients of the two materials are different, a cyclic mechanical stress develops and generates a microcrack. The crack expands over time under the thermal cycling, and when the resisting strength of the material is less than the applied stress, the fatigue failure occurs.

3.3.3 Humidity

Relative humidity, used as a humidity measure in scientific and engineering applications, is defined as a ratio of the amount of moisture present and the amount of moisture when the air is saturated. The latter one is dependent on temperature, and therefore, relative humidity depends on moisture content and the temperature. Humidity causes corrosion and short circuits. Corrosion is a gradual destruction of a metal, which can, furthermore, cause electrical performance and mechanical strength to deteriorate.

3.3.4 Voltage

When voltage is applied between two points of a component or a product, it is resisted by the dielectric strength of the material between the points. In an insulating material the current is small (therefore it is sometimes called leakage current), but it increases with the voltage. If the voltage reaches certain level, the insulator breaks down and the current increases rapidly. In conductors and electronic components, high voltage generates high current which may result in various failure mechanisms (next paragraph).

In addition, high voltage causes arcing which, furthermore, causes electromagnetic noise in neighboring components and wear-out of electrical contact surfaces.

3.3.5 Electrical current

Electrical current has same effects as temperature stress due to the fact that an electrical current flowing through a conductor produces heat in a conductive material. Heat is transferred to neighboring components that makes their temperature to rise. In addition, electrical current speeds up corrosion process and generates magnetic fields which interfere with neighboring electronic components.

3.3.6 Mechanical vibration

The most common vibration types are sinusoidal and random vibration. Sinusoidal vibration occurs at a predominant frequency whereas random vibration occurs in a wide range of frequencies. Since vibration is continuous changing of acceleration, vibration generates a cyclic stress. Moreover, the cyclic stress develops microcracks which can eventually result in fatigue failure. In addition, vibration causes mechanical wear i.e. attrition of mating materials in relative movement. Finally, vibration causes also loosening of connections which, furthermore, can lead to various failures such as leaking and deterioration of connection strength.

3.4 Failures of a fan

A cooling fan is a critical part in a frequency converter as it is in most electrical devices. It keeps the temperature of the device lower, and thus, prevents other components to fail due to high temperature. At the same time, the fan is one of the weakest links in electrical devices and therefore one of the major failure contributors to the devices (Tian 2006, Jin et al. 2012). Hence, reliability of a fan is a crucial factor in reliability of electronic products.

3.4.1 Fan failure classifications

Fan failures can be classified in several ways. Sidharth and Sundaram (2004) divide fan failures into fatigue failures and failures of associated electronics. Many authors, such as Tian (2006) and Jin et al. (2012) speak of electronic and mechanical failures depending on whether the failure occurs in a fan’s electronic part (a control circuitry, a motor and its electronic components) or mechanical part (a bearing, lubricant, a shaft, fan blades or a propeller / a impeller and a fan housing). Tian (2006) also divides failures into “hard failures” in which the fan stops functioning and “soft failures” (parametric failures), such as slower speed. Oh et al. (2010) examine fan failures according to in which major component they occur (a bearing, blades, a drive or a stator).

3.4.2 Fan failure criteria

Most often used signals through which the fan indicates a failure, are decrease in the rotation speed, increase in the input current and increase in the acoustic noise of the fan. Different manufacturers use different definitions for a fan failure regarding the limits of these quantities. IPC-9591 standard (2006) proposes the following fan failure criteria:

- rotation speed decreased by 15 %
- input current increased 15 %
- acoustic noise increased by 3 dB

Failure criteria by different manufacturers are listed in Table 2.

Table 2: Fan failure criteria

	RPM	Current, I	Noise	Others
IPC-9591	$\leq 0.85\ RPM_{original}$	$> 1.15\ I_{original}$	+3 dBA	Incorrect or erratic operation of electronic interface; Visible cracking of fan structure; Visible leakage of lubricant.
Company A	$< 0.9\ RPM_{original}$	$> I_{maximum}$	N/A	N/A
Company B	$< 0.9\ RPM_{original}$ / $> 1.1\ RPM_{original}$	$> I_{maximum}$	+3 dBA	Defects in fan components; Cannot operate at the lowest start up voltage in the spec.
Company C	$\leq 0.85\ RPM_{original}$	$> 1.15\ I_{maximum}$	+3 dBA	N/A
Company D	$< 0.85\ RPM_{original}$	$> I_{maximum}$	+3 dBA	N/A
Company E	$< 0.7\ RPM_{original}$	N/A	N/A	N/A
Company F	$< 0.85\ RPM_{original}$	$> 1.15\ I_{original}$	+3 dBA	No function.

3.4.3 Fan failure modes and mechanisms

When we are dealing with failures, we need to differentiate between failure mode and failure mechanism. Ohring (1998, p. 17-18) defines that failure mechanism is a physical, chemical, metallurgical and / or environmental phenomenon that causes the failure of a device. In contrast, failure mode is a recognizable indication by which a failure can be observed. A failure mode can be caused by one or more failure mechanisms. Failure modes, causes and mechanisms occurring in different parts of a fan, listed by Oh et al. (2010), are shown in Table 3.

Table 3: Fan failure modes, causes and mechanisms (Oh et al. 2010)

Failure site	Failure modes	Failure causes	Failure mechanism
Ball bearing	Seizure	Thermal overload	Lubricant deterioration
	Spalling	Cyclic loading	Fatigue
	Small furrows	Moisture	Corrosion
	Brinell mark	Mechanical overload	Yielding
Blade	Surface fouling Crack	Dust Cyclic loading	Adhesion Fatigue
Drive	Open circuit	High temperature	Interdiffusion
	Short circuit	Voltage bias, moisture	Dendritic growth
	Open circuit	Moisture	Corrosion
	Crack on solder interconnected	Thermal cycling, cyclic load	Fatigue
	Open circuit on wire bond	Thermal or mechanical shock	De-adhesion
Stator	Cracked and peeling winding wire film	Thermal overload, mechanical overload	Thermal aging of insulating materials

For prioritization of the failure mechanisms, Oh et al. (2010) have classified the failures into risk categories according to the occurrence and the severity of the failures (risk priority number = occurrence × severity). The data presented in Table 4 is achieved by past experience, stress analysis, accelerated tests and engineering judgment.

Table 4: Fan failure mechanisms and their risk levels (Oh et al. 2010). Occurrence criteria: 5 (frequent), 4 (reasonably probable), 3 (occasional), 2 (remote), 1 (extremely unlikely). Severity criteria: 5 (total product failure), 4 (loss of function), 3 (performance degradation), 2 (operable at reduced performance), 1 (minor nuisance). Risk priority number = occurrence × severity

Failure site	Failure mechanism	Occurrence	Severity	Risk priority number	Risk
Ball bearing	Lubricant deterioration	5	3	15	High
	Fatigue	1	3	3	Low
	Corrosion	2	3	6	Low
	Yielding	4	3	12	High
Blade	Adhesion	5	3	15	High
	Crack	3	3	9	Medium
Drive	Interdiffusion	1	4	4	Low
	Dendritic growth	1	4	4	Low
	Corrosion	1	4	4	Low
	Fatigue	2	4	8	Medium
	De-adhesion	1	4	4	Low
Stator	Thermal aging of insulating materials	2	4	8	Medium

We can observe from the table that there are three failure mechanisms with high risk: lubricant deterioration and yielding of the ball bearing and dust adhesion on the fan blades. The two highest are lubricant deterioration and dust adhesion. In addition, according to many authors (such as Oh et al. 2010, Jin et al. 2012 and Tian 2006), the ball bearing is the most fragile part of the fan, i.e. a so called bottleneck component with the highest risk of failure. Therefore, in this work we are going to concentrate most on the life expectancy of the ball bearing.

3.4.4 Physics of main failure mechanisms

Deterioration of lubricating grease occurs due to thermal overload. This deterioration can be either physical or chemical degradation process. The physical degradation is caused by evaporation of lubricant, and chemical degradation either by antioxidant consumption or lubricant oxidation. Lubricant deterioration may result in seizure, a state in which relative motion between bearing parts stops due to increased friction. Fig. 19 shows parts of a ball bearing as a result of seizure, an inner ring and a cage and balls, respectively. We see all these parts have damaged by melting. (Oh et al. 2010)

Fig. 19: Seizure of a ball bearing a) an inner ring b) a cage and balls (NSK Americas b)

A ball bearing is more vulnerable for mechanical overloads during its non-operating condition rather than operating condition due to the fact that viscosity of the lubricant is higher during the operating condition. Mechanical overload which exceeds the yield point of the bearing material can cause a permanent indentation, called Brinell mark. In Fig. 20 we see an inner and an outer ring of a ball bearing with spherical cavities, i.e. Brinell marks. (Oh et al. 2010)

Fig. 20: Brinell marks a) an inner ring b) an outer ring (NSK Americas a)

Blades of a fan are often liable for dust in the operation environment. Dust particles accumulate on the surface of fan blades as a result of a phenomenon called adhesion.

Several theories exist for explaining adhesion mechanism: physical absorption, chemical bonding, electrostatic and mechanical interlocking. The challenge of evaluating life expectancy limited by dust adhesion is that a unifying model of physics of various kinds of dust particles does not exist. Hence, influence of dust on lifetime cannot be calculated.

3.5 Evaluation methods for lifetime and reliability of a fan

Different methods for evaluating reliability of fans exist. Here we are going to discuss calculation methods for lubricant deterioration and fatigue failure, usage of Weibull distribution, accelerated tests, reliability tests and failure identification using vibration signal.

3.5.1 Bearing life equations

The life expectancy of a ball bearing for lubricant deterioration can be calculated with the grease life equation, used by Oh et al. (2010) and originally presented by bearing manufacturer NSK (2011, p. A 107):

$$\log L_{50} = 6{,}54 - 2{,}6\frac{n}{N_{lim}} - \left(0{,}025 - 0{,}012\frac{n}{N_{lim}}\right)T \tag{3.2}$$

where L_{50} is the time which 50 % of a bearing sample functions without a failure (h), n is the rotation speed of a fan (rpm), N_{lim} is limiting speed with grease lubrication (rpm) and T is the operating temperature of the bearing (°C). Limiting speed depends on the dimensions of the bearing and thus, on its load. Limiting speed can be determined from the inner and the outer diameters of the bearing by using a bearing data table. The diameters were defined in Fig. 17. The coefficients of the equation are for general purpose grease. NSK (2011, p. A 107) has provided coefficients also for wide-range grease:

$$\log L_{50} = 6{,}12 - 1{,}4\frac{n}{N_{lim}} - \left(0{,}018 - 0{,}006\frac{n}{N_{lim}}\right)T \tag{3.3}$$

The life expectancy of a ball bearing for fatigue failure can be calculated with the equation provided by ISO 281 standard (2007):

$$L_{10} = \left(\frac{C_r}{P_r}\right)^3 \tag{3.4}$$

where L_{10} is the time which 90 % of a sample of bearings will achieve or exceed without a failure (h or revolutions), C_r is (dynamic) load rating (N) and P_r is equivalent radial load rating (N). Oh et al. (2010) calculated as an example this life expectancy for a fan from a catalog using values given in the catalog, and got 25 000 years as a result. The fact that the value is gigantic is reasonable since the equation calculates the life expectancy *for fatigue failure,* and fatigue is not one of the most significant fan failure mechanisms.

If a ball bearing is used at high temperatures, i.e. if the temperature of the bearing is 125 °C or higher, temperature adjustment can be made for load rating C_r in the previous equation.

$$C_t = f_t C_r \tag{3.5}$$

where Ct is load rating after temperature correction, f_t is a temperature coefficient (discovered from a manufacturer, such as NSK) and C_r is load rating before temperature adjustment (NSK 2011, p. A 26). Equation (3.4) can be also adjusted due to a higher reliability requirement than 90 %, special bearing properties such as improvements in bearing steel and notable operating conditions.

$$L = a_1 a_2 a_3 L_{10} \tag{3.6}$$

where L is life expectancy after adjustment, a_1 an adjustment factor for reliability, a_2 an adjustment factor for special bearing properties, a_3 an adjustment factor for operating conditions and L_{10} is life expectancy before adjustment. Coefficient a_3 can be used to adjust the equation for various factors, especially for lubrication, and it can be either greater or smaller than one. (NSK 2011, p. A 27)

Equation (3.4) has some noteworthy advantages. It calculates L_{10} which is a commonly used lifetime metric. In addition, the equation is adjustable in different ways, and hence, several factors of a particular fan and its operating conditions can be taken into account.

However, even though all the factors could be determine correctly, the equation nevertheless calculates life expectancy limited by fatigue failure which is not one of the most significant fan failure mechanisms, as mentioned.

In contrast, Equation (3.2) calculates life expectancy for lubricant deterioration which is indeed the most significant failure mechanism of the ball bearing. Moreover, this equation has properties which make it useful for our research. As mentioned, the lifetime evaluation method used in the program developed in this work, has to be based on quantities that are measured from the studied application, ACS880-01 frequency converter under its normal operating condition. The variables of Equation (3.2) are values known through measurements and properties of the fan or of the bearing which can be discovered from the component manufacturer. For these reasons we have chosen this method.

3.5.2 Weibull distribution

Weibull distribution is a widely used model in reliability and failure examination. Cumulative density function of Weibull distribution, shown in Fig. 21, can be written as follows (Jin et al. 2012):

$$F(t) = 1 - e^{-\left(\frac{t}{\alpha}\right)^{\beta}} \tag{3.7}$$

where t indicates time, α is a scale parameter, also called characteristic life and β is a shape parameter. When this model is used in calculation of life expectancy, accuracy of the calculation depends heavily on the value of β. Different manufacturers have different recommendations for the value. Jin et al. (2012) suggest that an effective way to determine the value of β is to let a proper number of fans run at a certain temperature at their rated input voltage until all of them fail and plot the lifetime data on Weibull probability paper to discover the accurate β. If $\beta < 1$, the failure rate decreases over time; if $\beta = 1$, the failure rate is constant over time; and if $\beta > 1$, the failure rate increases over time.

By inserting $F(t) = 0{,}1$ (reliability of 90 %) and $t = L_{10}$ in (3.7) we get:

$$L_{10} = \alpha \left[ln \frac{1}{1 - 0{,}1} \right]^{\frac{1}{\beta}} \tag{3.8}$$

Mean time to failure can be calculated as follows (Jin et al. 2012):

$$MTTF = \alpha\Gamma\left[1 + \frac{1}{\beta}\right] \tag{3.9}$$

where α and β are as above and Γ is gamma function. Gamma function is a special function (i.e. other than algebraic or transcendental functions) also known as Euler's integral of the second kind. Gamma function is an extension of the factorial function with its argument shifted down by 1. It is analyzed, for instance, by Ramana (2007, p. 11.1).

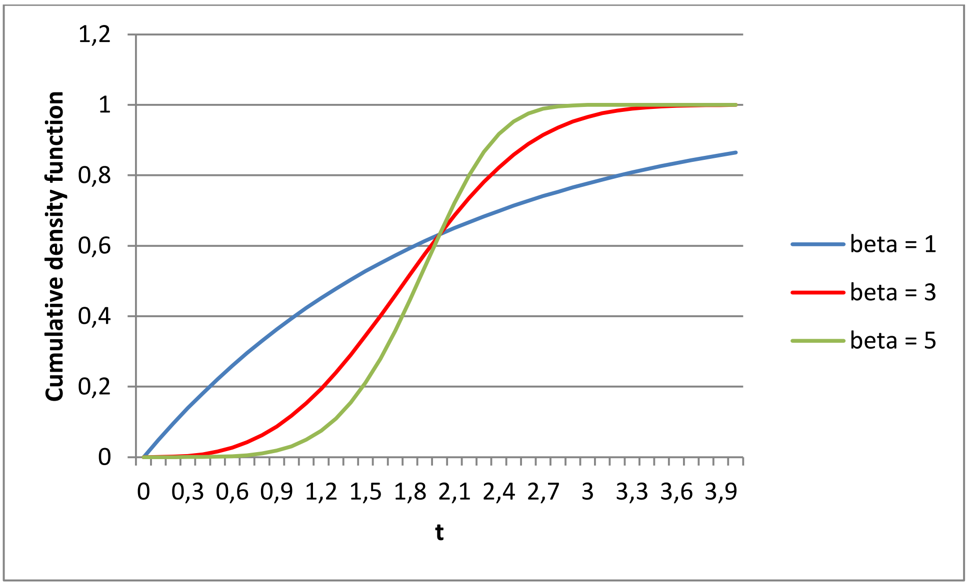


Fig. 21: Cumulative density function of Weibull distribution when α = 2

In addition, Weibull distribution can be used for adjusting lifetime quantities to a required reliability. Generally, reliability of 90 % is used for determining the life expectancy of a bearing, i.e. L_{10} is calculated. However, sometimes a higher reliability level is required, for instance due to higher risk for a human or for a device, or another level is known, such as when using Equation (3.2). The relation derived from Weibull distribution is as follows:

$$\frac{L_R}{L_{10}} = \left[\frac{\ln\frac{1}{R}}{\ln\frac{1}{0{,}9}}\right]^{\frac{1}{1{,}17}} \tag{3.10}$$

where L_R is life expectancy at the required reliability, L_{10} is life expectancy at 90 % reliability and R is the required reliability (Sharma 2005, p. 594). Consequently, using this formula, the coefficient between L_{50} and L_{10} is 5,0035 which means that L_{10} can be calculated from L_{50} by dividing it by five.

3.5.3 Accelerated tests

Since the lifetime of a fan at normal operating conditions is quite long, usually several years, it is not useful or even possible to examine fans' lifetime by testing them at normal operating conditions until they fail. Therefore, the accelerated life test (ALT) is widely used method for evaluating life and reliability issues, such as lifetimes and failure rates. In such a test, the lifetime of a product is shortened by exposing the product to operating conditions with more severe stress level than in the product's normal operating conditions. The higher stress level can be achieved by using, for instance, higher temperature, voltage, humidity, pressure or vibration (Kececioglu 2002, p. 605). If the test is properly designed, failures which would not occur at normal operating conditions do not occur in the test either (Misra 2008, p. 545). In fan tests, temperature is an effective stress and it is the most commonly used stress in accelerated tests (Jin et al. 2012).

Main concern in accelerated tests is to have a proper value of the acceleration factor. The acceleration factor (AF) is defined as a ratio of the lifetime at field conditions (L_{use}) and the lifetime at test conditions (L_{test}) i.e. at higher stress level:

$$AF = \frac{L_{use}}{L_{test}} \tag{3.11}$$

Therefore, when temperature is used as an accelerating stress, the value of the acceleration factor should correlate with the real effect of temperature. IPC-9591 standard (2006) suggests for the acceleration factor:

$$AF_{IPC} = 1{,}5^{\left(\frac{T_{test}-T_{use}}{10}\right)} \tag{3.12}$$

where T_{test} is the testing temperature used in ALT and T_{use} is the operating temperature where the fan is used. The equation implies that a fan's lifetime drops by a factor of 1,5 for every 10 °C increase in temperature. Hence, life expectancy at a higher temperature

$L_{10,warmer}$ can be solved from the life expectancy at a lower temperature $L_{10,colder}$ and the acceleration factor as follows:

$$L_{10,warmer} = \frac{L_{10,colder}}{1{,}5^{(T_{warmer}-T_{colder})/10}} \tag{3.13}$$

Different fan manufacturers use different values for the acceleration factor based on their own experience.

The Arrhenius model

When the accelerating variable in the test is temperature, the Arrhenius model can be used for defining the acceleration factor. The Arrhenius model expresses the relation between a component's or a device's lifetime (*L*) and the temperature (*T*):

$$L = Ce^{E_a/kT} \tag{3.14}$$

where E_a is activation energy (eV), k Boltzmann's constant (eV/K) and C is a non-thermal constant. Activation energy is the minimum amount of energy molecules have to carry to cause a reaction leading to a failure mechanism. Therefore, the activation energy depends on the failure mechanism being examined in addition to the component or the device. For most failure mechanisms in electronic components and devices, the activation energy is between 0,3 and 1,5 eV. When we determine the lifetime at field conditions (L_{use}) and the lifetime at test conditions (L_{test}) with Equation (3.14), we can solve the acceleration factor as a ratio of them:

$$AF_{ARR} = e^{\frac{E_a}{k}\left(\frac{1}{T_{use}}-\frac{1}{T_{test}}\right)} \tag{3.15}$$

(Kececioglu 2002, p. 607, Yang 2007, p. 254)

3.5.4 Reliability tests

Reliability tests can be used for evaluating whether a value of life expectancy, for instance given by a manufacturer, is reliable or not. Jin et al. (2012) introduce two methods for this purpose based on Weibull distribution: zero-failure test and test with failures.

A zero-failure test reveals if a life expectancy is valid with a certain confidence level. In the method, a value for a test time is calculated from the life expectancy. This value indicates the time which all of the fans in the test have to function without a failure, for that the life expectancy would be realistic. The test time t_{test} can be calculated either by means of the exponential or the binominal distribution. By using the exponential distribution we get with 90 % confidence:

$$t_{test} = \alpha \left[\frac{2{,}303}{n}\right]^{\frac{1}{\beta}} \tag{3.16}$$

where α and β are as in (3.7) and n is the number of tested fans. By using the binominal distribution the result is otherwise the same, just the constant in the numerator is 2,3025. The calculation process of the method is performed by solving first the life expectancy at the test temperature $L_{10,test}$ from the claimed life expectancy $L_{10,use}$ with the help of Equation (3.13). Then, the value of the scale parameter α at the test temperature is solved from Equation (3.8), and moreover, the test time t_{test} is solved from Equation (3.16) using the discovered value of α. Using this method requires the researcher to have proper values for the shape parameter β, for instance, from a manufacturer, and for the number of tested fans.

Test with failures is a method in which fans are being run until a preordained number (for instance 5 or 10) of them have failed. The failure data is plotted in Weibull distribution paper to discover the values of α and β. Then L_{10} or $MTTF$ can be calculated (Equations (3.8) and (3.9)) and compared to the values given by the manufacturer. Advantage of this method is that the value of β does not need to be estimated. However, disadvantages are long duration of the test (at least a year) and high cost.

3.5.5 Failure identification using vibration signal

Miao et al. (2011) introduce a method for assessing fan degradation by using vibration signal. Typical failures of a ball bearing come up as local faults on the inner race, the outer race, the cage or the rolling elements. The principle of the method is that if there is a local fault in some of these components, the corresponding characteristic frequency and its harmonics can be observed in the spectrum of the vibration signal. The characteristic frequencies can be calculated as follows:

Ball spin frequency:

$$BSF = f_{rR} = \frac{bf_r}{2a}\left[1 - \left(\frac{a}{b}\cos\varphi\right)^2\right] \tag{3.17}$$

Ball pass frequency of the outer race:

$$BPFI = f_{rI} = \frac{nf_r}{2}\left(1 + \frac{a}{b}\cos\varphi\right) \tag{3.18}$$

Ball pass frequency of the inner race:

$$BPFO = f_{rO} = \frac{nf_r}{2}\left(1 - \frac{a}{b}\cos\varphi\right) \tag{3.19}$$

Fundamental train frequency:

$$FTF = f_{rC} = \frac{f_r}{2}\left(1 - \frac{a}{b}\cos\varphi\right) \tag{3.20}$$

where f_r is the rotation speed of the bearing shaft (Hz), n is the number of rolling elements, a is the mean diameter of the rolling elements (mm), b is the pitch diameter of the bearing (mm) and φ is the contact angle (°).

The challenge of using the vibration signal as a failure indicator is that when a local failure occurs in the ball bearing, the vibration signal gets modulated. Therefore filtering and demodulation system is necessary. In the method proposed by Miao et al. (2011) DWT (discrete wavelet transform) and Hilbert transform are used for this purpose.

The process is implemented as follows: loading the original signal; pre-processing the original signal to remove the trend and the DC component; decomposing the signal into different bands using discrete wavelet transform; demodulation of the signal using Hilbert transform; spectrum analysis and identifying the fault characteristic frequency components.

Miao et al. (2011) conducted an experiment in which they ran an unused fan and measured the vibration signal before and after a 72-hour accelerated stress period. The results showed that in the beginning there were not fault-related characteristic frequencies in the spectrum but at the end of the experiment, several of those frequencies and their harmonics appeared in the spectrum. The proposed method is advanced way for on-line health evaluation of fans, yet, it requires sophisticated signal processing.

4 The program for evaluating the life expectancy of a fan

In this Chapter we are going to introduce the program implemented by the author as a concrete part of this work. A version of the program is implemented with Codesys software using Structured text programming language. Purpose of the program is to give the user or the maintenance information on how long a fan is expected to function. As we have discussed, a ball bearing is the weakest component of the fan, i.e. the component which has the highest probability to fail first, and lubricant deterioration is its main reason for failure. Therefore, the program uses an equation which calculates the life expectancy of a ball bearing for lubricant deterioration. First, we are going to analyze the equation more accurately. Second, we introduce the calculation algorithm and the structure of the program. Finally, we are going to view the limitations of the program, and moreover, the prospects of it.

4.1 Characteristics of the bearing life equation

As we discussed in Chapter 3.5.1, the life expectancy of a bearing for lubricant deterioration can be calculated with Equation (3.2). This equation (called here bearing life equation) presents the relation between the median value of the bearing life and two variables: the rotation speed of the fan and the operating temperature of the bearing. We

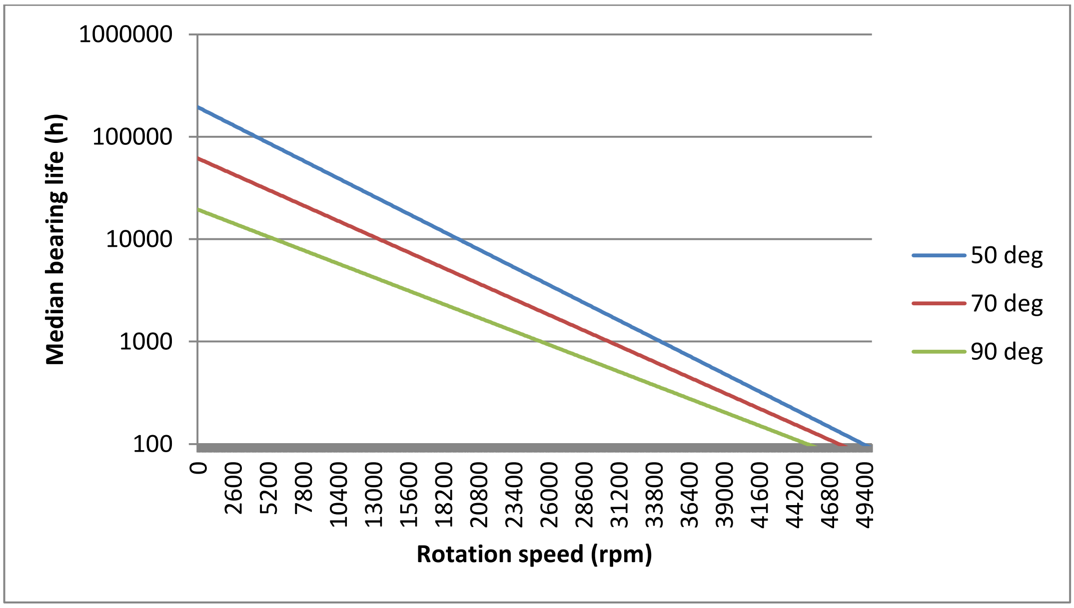


Fig. 22: A bearing's life expectancy vs. rotation speed, Eq. (3.2); a shielded-type bearing with the inner diameter of 12 mm, the outer diameter of 24 mm and N_{lim} of 30 000 rpm

can examine this relation by assuming one of the variables to be constant at a time. Fig. 22 shows the bearing life expectancy's dependence on the rotation speed at three different constant temperatures.

From each curve in Fig. 22 we see that the larger the rotation speed is, the shorter the life expectancy is, and the relation looks linear when the vertical axis is logarithmic. In addition, we can observe that the larger is the rotation speed, the smaller is the influence of a temperature change on the life expectancy. Fig. 23 shows the bearing life expectancy's dependence on temperature at three different rotation speeds.

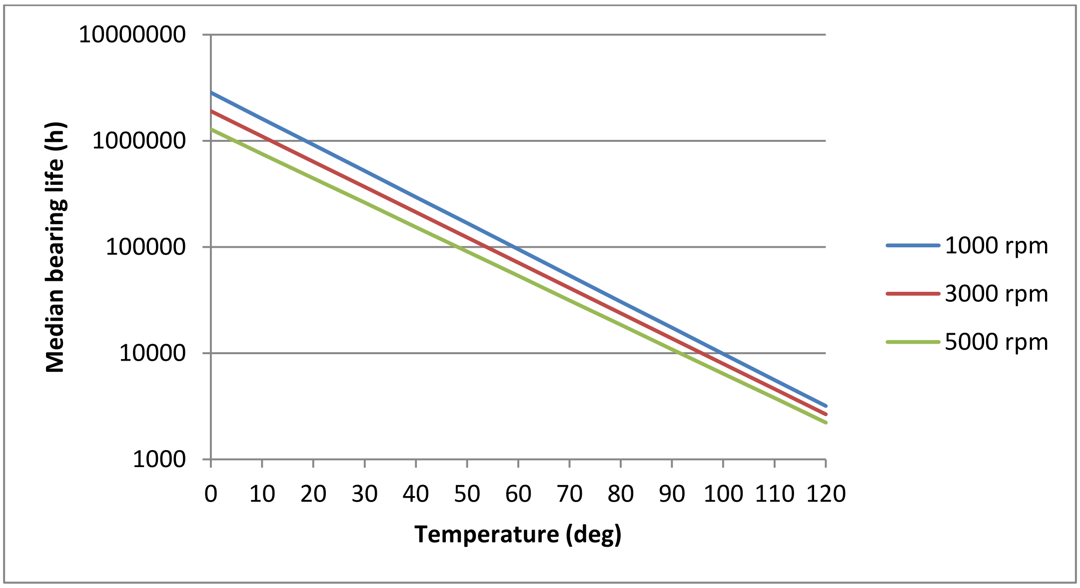


Fig. 23: A Bearing's life expectancy vs. temperature, Eq. (3.2); a shielded-type bearing with the inner diameter of 12 mm, the outer diameter of 24 mm and N_{lim} of 30 000 rpm

The relation between the life expectancy and the temperature is similar to the relation between the life expectancy and the rotation speed. From the curves in Fig. 23 we see that the higher the temperature is, the shorter the life expectancy is, and the relation looks linear when the vertical axis is logarithmic. In addition we can observe that the larger is the temperature, the smaller is the influence of a rotation speed change on the life expectancy.

4.2 The calculation algorithm

Fig. 24 shows the principle of the program. The input quantities are placed on the left side of the box and the output quantities on the right side. The input quantities are the frequency converter's properties and parameters, based on measurements and stored by the counters within the device. The output quantities are parameters that include the useful information regarding the fan's life expectancy and they are given to the user or the maintenance as a result of the calculation.

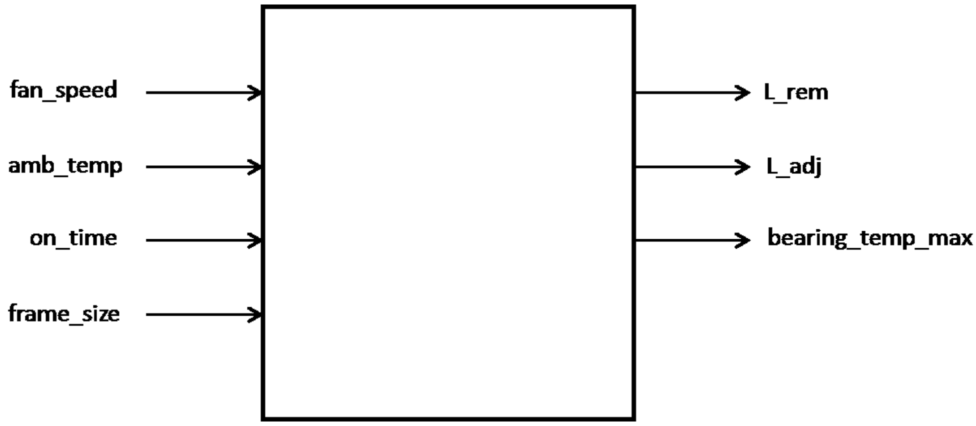


Fig. 24: The input and the output quantities of the program

4.2.1 The input quantities

Changing quantities:

- `fan_speed`: rotation speed of the fan
- `amb_temp`: temperature of the ambient
- `on_time`: time of the fan's usage

Quantities needed to define only at the beginning of the fan's usage:

- `frame_size`: frame size of the frequency converter; needed for defining the following constants:
    - `temp_const`: temperature difference between the ambient temperature and the bearing temperature
    - `N_lim`: the bearing's limiting speed with grease lubrication

4.2.2 The output quantities

- `L_rem`: expectancy of the remaining life (a value in which loading history is taken into account, defined below)
- `L_adj`: adjusted value of life expectancy (a value in which loading history is taken into account, defined below)

- `bearing_temp_max`: the largest value of experienced bearing temperature

4.2.3 The calculation method

Since the bearing life equation gives a life expectancy value based on momentary values of fan speed and temperature, it does not take into account the loading profile i.e. the former values of these quantities. For instance, let's assume a fan is used at a certain speed and at a certain temperature, and after half a year an air conditioning is installed into the operating site making the bearing temperature drop by 20 degrees. After the installation the value given by the equation is too optimistic since the loading has been severer until the installation. Hence, the program has to include an algorithm which calculates the effect of the loading and adjusts the life expectancy according to the loading history.

Here we use a method that we call cumulative distribution percents. The method is illustrated in Fig. 25. When the usage of a fan begins, the percent value of the bearing is 0 % and when 100 % is reached, the fan is expected to fail (due to the bearing's lubricant deterioration failure). The bearing accumulates the percents linearly when the fan is in use, and the rate of accumulation is determined by the severity of the loading. That is to say, the severer loading the steeper slope. The example curve shown in Fig. 25 is introduced more accurately after presenting the calculation process.

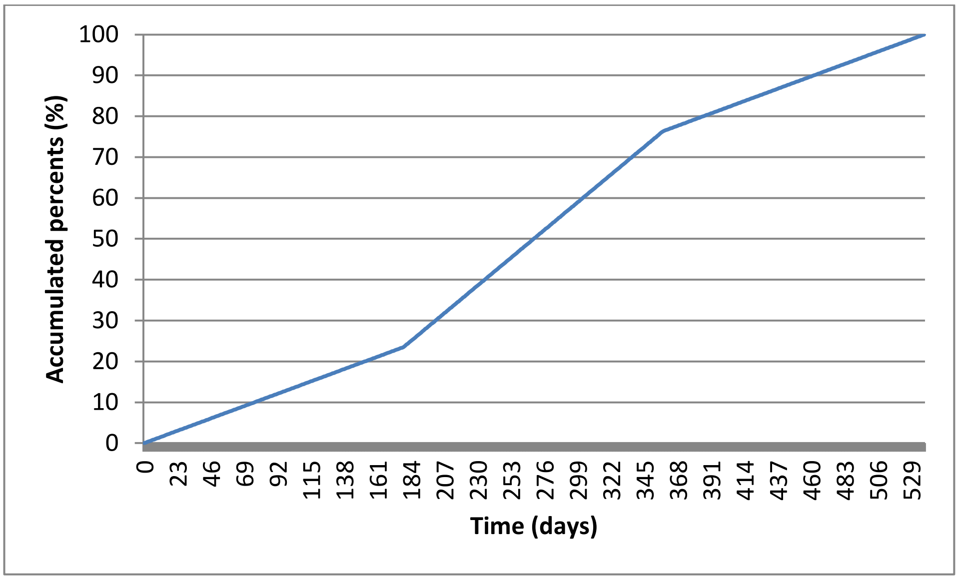


Fig. 25: An example of a loading profile of a fan

The calculation process of the algorithm is implemented as follows, and it is repeated at the intervals of t (defined later as t_2).

- `L_mom` is calculated from Equation (3.2) by using momentary values of fan speed and the average of bearing temperature so that `L_mom` = L_{50}.
- `k` (slope, how severe is the loading):

$$k = \frac{100\ \%}{L_{mom}} \tag{4.1}$$

- `y` (amount of accumulated percents) is calculated recursively:

$$y_n = y_{n-1} + k_n t \tag{4.2}$$

  where t is time interval between updates and n is an integer.

- `L_rem` (expectancy of the remaining life, illustrated in Fig. 27):

$$L_{rem} = \frac{100\ \% - y}{k} \tag{4.3}$$

- `L_adj` (adjusted value of life expectancy, illustrated in Fig. 26):

$$L_{adj} = L_{rem} + on\_time \tag{4.4}$$

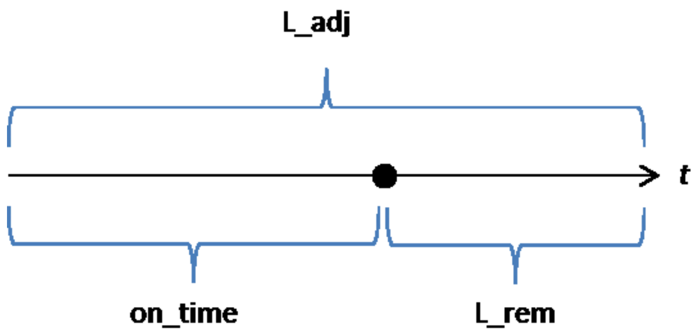


Fig. 26: The connection between variables L_adj, L_rem and on_time

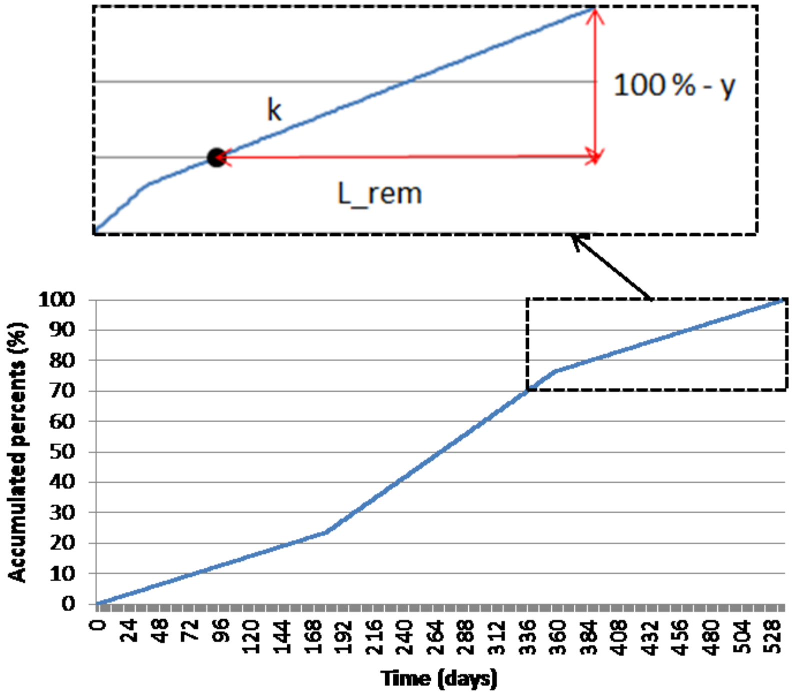


Fig. 27: Calculation of L_rem

The example curve shown in Fig. 25 is derived from the following imaginary case: the bearing temperature is constant 70 °C all the time; the rotation speed of the fan is 3000 rpm for the first third; 5000 rpm for the second third and 3000 rpm for the last third. Let's examine a non-contact sealed type bearing whose inner diameter is 28 mm and outer diameter 68 mm and thus, N_{lim} is 10 000 rpm (NSK 2011, p. B 10). We see that the slope, calculated as presented in Equation (4.1), is constant as long as the loading stays the same; gets steeper when the fan speed changes into 5000 rpm and returns to the previous value when the fan speed returns to 3000 rpm.

Fig. 28 illustrates how the algorithm adjusts the value of life expectancy according to the loading history. The same loading case is still used. The green dashed curve presents the value of `L_mom` (the life expectancy based on momentary values of fan speed and the average of bearing temperature) and blue solid curve the adjusted value of life expectancy, `L_adj` (i.e. the value in which the loading history has been taken into account). For the first third the loading is constant, and therefore, `L_mom` and `L_adj` are equal. If the loading stayed the same for the whole bearing life, these variables would remain unchanging equal constants all the time. For the second third, `L_mom`, as it is, is set according to the prevailing loading, but `L_adj` does not get as low since it "remembers" the loading has not been equally severe from the beginning. For the last third, `L_mom` gets again a value according to the prevailing loading (the same value as for the first third since the loading returns to the same state as in the beginning) but `L_adj` does not get as high, again due to the fact that it takes into account the experienced loading history.

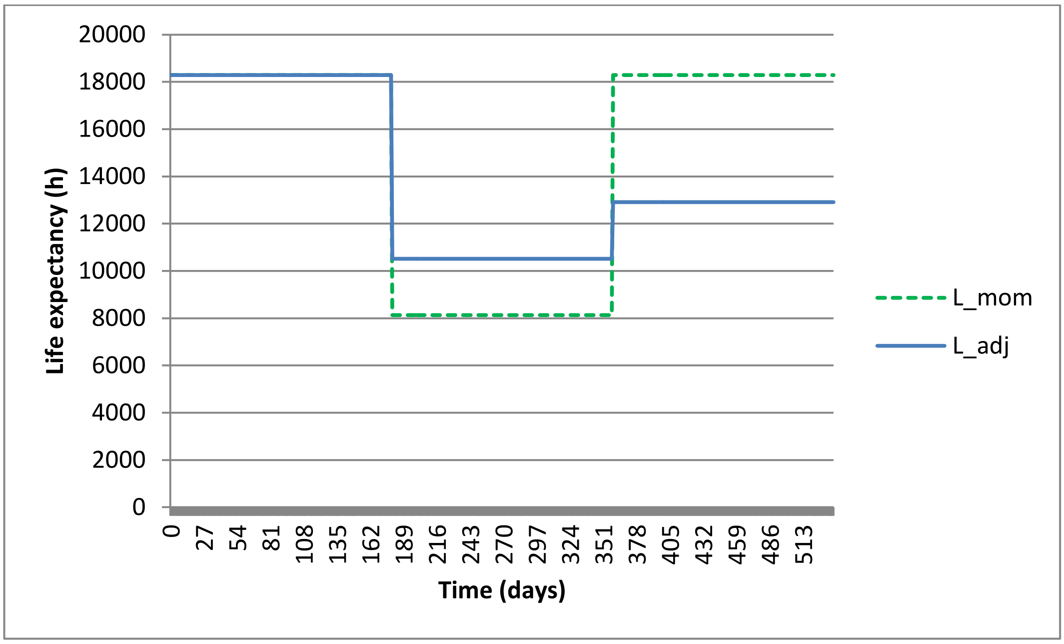


Fig. 28: Life expectancy based on momentary input values (green dashed curve) and adjusted life expectancy (blue solid curve) in which loading history has been taken into account

4.2.4 Bearing temperature vs. ambient temperature

Regarding temperatures, the following issue has to be solved in the algorithm: the temperature of the bearing is needed for calculating the life expectancy but there is no such a parameter to be used as an input value. Consequently, the program has to take the ambient temperature as an input value and to calculate the bearing temperature from that value. There is a rule of thumb that the temperature of the bearing is 15-20 degrees higher than the temperature of the air surrounding the bearing.

When using this rule of thumb, we need to take into account the location of the fan. As we discussed in Chapter 2.5, in ACS880-01 frequency converters the location of the fan depends on the frame size of the device. In frames from R1 to R5 the main fan is located at the top of the device, whereas in frames from R6 to R9 it is located at the bottom of the device. The ambient temperature is measured at the bottom of the device and hence, when the fan is located at the bottom of the device, the ambient temperature is approximately the temperature of the air surrounding the bearing. In this situation the bearing temperature can be calculated from the ambient temperature using the rule. In contrast, when the fan is located at the top of the device, the ambient temperature does not equal the temperature of the air surrounding the bearing. There are a heat sink and other components between the top and the bottom of the device, and therefore, temperature is higher at the top. Thus, we need to know the temperature difference between these points and add it to the rule's constant.

For this purpose we have consulted reports of heat runs executed for devices of each frame size. In those heat runs it was tested that the temperatures of the devices' parts and surfaces do not exceed the temperature limits of the relevant safety standards when the device is at the worst case scenario in respect of input values. From the reports we have investigated the temperature values measured from the top and the bottom of the devices. We use a symbol `temp_const` for indicating the constant needed to add to the ambient temperature to discover an estimate for the bearing temperature.

4.3 The structure of the program

Function of the program is divided into two tasks (subprograms): Main program and Temperature program. Temperature program is repeated at the intervals of t_1 and Main program at the intervals of t_2 ($t_2 > t_1$) (discussed in Chapter 4.5). The block diagram of the program is shown in Fig. 29.

Global variables

Varibles `bearing_average_temp` and `i` are defined global variables since they are used in both tasks.

Temperature program

This program finds out the largest value of temperature the bearing has experienced during its usage by observing the ambient temperature parameter. This value is stored as meaningful information even though it is not used in calculation. Temperature program also calculates **the average of the temperatures the bearing has experienced between life expectancy updates**. This average value is used for calculating a new value of life expectancy in Main program. The `bearing_average_temp` is calculated recursively:

$$T_{ave,i} = \frac{i-1}{i} T_{ave,i-1} + \frac{1}{i} T_i \tag{4.5}$$

where `i` is an index, an integer which grows constantly between life expectancy updates starting from 1.

Main program

Main program updates life expectancy values at certain intervals. The program follows the logic introduced in the calculation method section. First, the program reads the values of the fan speed parameter and the on time parameter. Second, it performs the calculation process as discussed to find out the output values `L_rem` and `L_adj`. Finally, Main program resets index `i` to 1 and `bearing_average_temp` to 0.

4.4 The limitations of the program

In this passage we discuss the limitations the program has. Some of them are related to the bearing life equation used in the algorithm and some to the algorithm.

4.4.1 The limitations of the equation

As we have discussed, the program uses the bearing life equation provided by NSK in the calculation algorithm. As a first limitation, the equation is constructed for a deep groove ball bearing, which is the most common type of rolling bearings. Consequently, if another bearing type is used, the results may not be valid.

Second, the equation calculates the life expectancy of the weakest component of a fan (a ball bearing) for its main failure reason (lubricant deterioration). Hence, it is obvious that if a ball bearing fails due to another reason or if a failure occurs at another component of the fan, the program cannot predict the failure.

Furthermore, NSK has provided the coefficients of the equation for general purpose grease and for wide-range grease. As a result, if another grease type is used, the coefficients may not be valid.

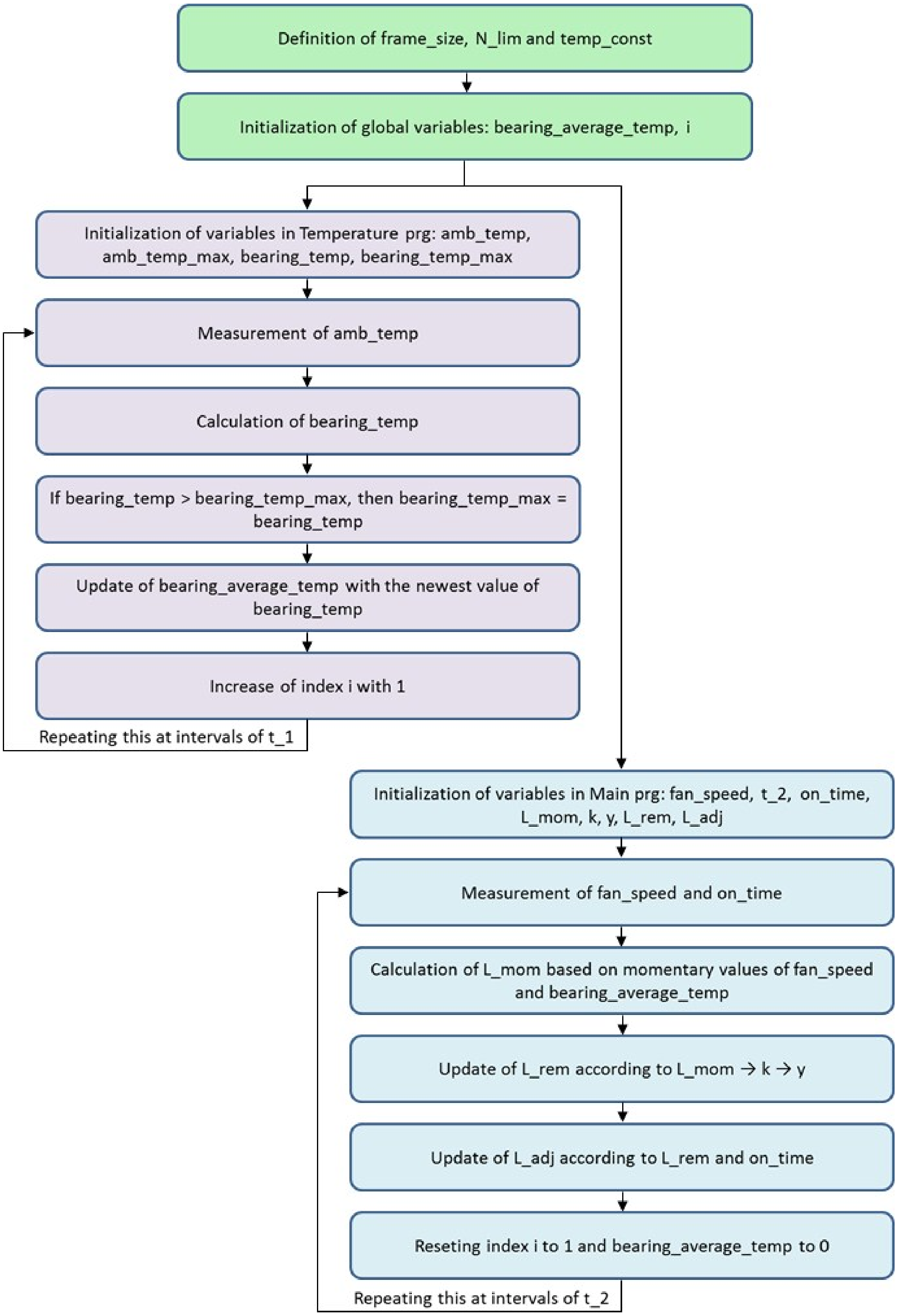


Fig. 29: The structure of the program

4.4.2 The limitations of the algorithm

The calculation process of the algorithm is based on the process occurring when the fan is in the operating condition, i.e. when it is in use. This has two major consequences. First, the algorithm does not take into account the process occurring when the fan is in the non-operating condition. The non-operating condition indeed consumes the remaining lifetime of the fan, also by contributing lubricant deterioration. Yet, the limitation is reasonable since there are many unsolved questions regarding the non-operating condition. How much being in the non-operating condition influences the lifetime of the fan compared to the operating condition? Which factors it depends on? What is the influence of keeping the fan in the non-operating condition for a long time without turning it on for a while?

Second, the algorithm does not take into account the processes of turning the fan on and off. Nevertheless, the problem is clear: we don’t have accurate data of the influence of these processes. More unsolved questions arise. How much turning the fan on and off influences its lifetime? Does it wear the fan more if it is turned on and off frequently? What is the influence of running the fan for a long time without turning it off for a while?

Moreover, one of the limitations of the algorithm is that there are environmental factors influencing the fan that the algorithm does not take into account. Major quantities, the temperature of the bearing and the rotation speed of the fan, are used as input values, and also changes in the input voltage of the fan are considered through the rotation speed. Yet, factors such as humidity, vibration and dust are not taken into account. This issue, for instance with dust, cannot be solved simply by adding some coefficients to the equation according to the amount of dust. As we saw in Chapter 3.4.3, dust adhesion is a failure contributor in fan’s blades, not in the bearing. We still need to remember that the equation calculates the life expectancy of the ball bearing for lubricant deterioration. Therefore, if we would like to add the influence of dust to the equation, we should know how the amount of dust contributes lubricant deterioration. The same goes with all other factors: for adding the influence of a factor to the equation, contribution of the factor to this particular failure mechanism should be known.

Finally, calculation of the bearing temperature from the ambient temperature is an approximation which may be inaccurate. As discussed in Chapter 4.2.4, temperature differences needed in the calculation are discovered from the heat run reports, and we cannot know if temperature behavior at real operating conditions correlates with the behavior observed in these tests.

4.5 The future of the program

The program constructed by the author has been implemented with Codesys software for a demo device. ABB has expressed their interest for implementing the program to their software interface for real devices that are sold to customers. In that interface, there is a greater variety of input signals available, not only the ones set as parameters, available for test applications such as Codesys programs. Consequently, the prospects for implementing a practical program are better. Here we list some issues regarding the implementation of the program to the software interface.

In the Codesys program, the rotation speed of the fan has to be inputted as a relative value (as percentage from maximum) and then convert it into an absolute value in the algorithm using the value of maximum speed, discovered from the fan’s specification. In contrast, in the software interface, the rotation speed of the fan may be possible to input directly as an absolute value.

Since the Codesys program is used only with (similar) demo devices, variables regarding the device’s properties used in the algorithm, have been set for these particular devices. When the algorithm is implemented for devices of all frame sizes, it has to include a kind of if-block which determines the properties, specifically the bearing’s limiting speed with grease lubrication and the temperature constant for discovering the bearing temperature from the ambient temperature, according to the frame size of the device.

Moreover, when the program is implemented to the software interface, the product development specialists have to consider proper values for the time intervals at which Main program and Temperature program are repeated. In the Codesys implementation, the repetition interval of Main program had to be set at 1 s simply because one second is the longest option for the time interval in the software. In practice, this repetition interval does not need to be that short; no advantages are achieved by updating the life expectancy value that often. On the other hand, Temperature program calculates the average of the temperatures experienced by the bearing between two life expectancy updates made in Main program, and hence, the repetition interval of Temperature program has to be a suitable proportion of the one of Main program. In the Codesys implementation this interval was set at 10 ms. In practice, this repetition interval does not need to be that short either. The length of this interval depends on how often the product development specialists prefer the program to observe changes in the temperature.

As discussed, the bearing life equation used in the algorithm calculates the median value of life expectancy (L_{50}) which occurs when 50 % of fans in a sample have failed. Generally, life expectancy is indicated with time to 10 % failure (L_{10}), i.e. 10 % of fans fail before this time is reached. Consequently, probably product development specialists prefer the program to calculate the latter metric. As presented in Chapter 3.5.2, the conversion between these metrics can be done easily by using Weibull distribution, that is to say, by dividing L_{50} by 5,0035.

In addition, NSK (2011, p. A 107) recommends that when the bearing temperature in Equation (3.2) is below 70 degrees, 70 degrees should be used in calculations to avoid too optimistic results. On the other hand, according to NSK representative (2012), at temperatures up to 70 degrees the grease functions satisfactorily in terms of grease life. Consequently, the product development specialists have to consider whether they set the limit at 70 degrees.

Regarding the verification of the program, there is a major challenge. Normal lifetime of a fan is several years, and hence, validity of the results calculated by the program may not be possible to see in the short term. ABB has proposed performing a pilot case for verifying the program. In such a case, the program would be implemented to the software interface of a number of devices, and the results would be observed by the maintenance as long as validity of them is uncertain. After accomplishing the verification, the results calculated by the program would be visible also to end users. Executing an accelerated life test for verifying the program, has been proposed as well by ABB.

5 Conclusions

In this thesis we have examined the lifetime and reliability of a frequency converter's cooling fan. A fan is a crucial element in a frequency converter, as it is in many electrical devices. When an electrical device is used, heat losses are generated. Heat causes several failure mechanisms and accelerates wear of materials making the lifetime of components shorter and hence, the temperature has to be kept low enough. On the other hand, a fan is also a device with wearing parts and limited lifetime. In this work we have aimed to discover the main failure contributors to a fan and to find a proper method for prognosticating a fan's lifetime.

We have examined different failure mechanisms of a fan. As a result we have discovered that in a fan, a ball bearing is the component which most probably fails first. Moreover, in a ball bearing, the failure mechanism with the highest risk, in respect of occurrence and severity, is lubricant deterioration. In addition, we have discussed different methods for evaluating a fan's lifetime. There are techniques such as calculation methods for certain failure mechanisms, methods based on Weibull distribution and accelerated tests. In this work we have searched for a method which can be used in the studied application, ACS880-01 frequency converters under their normal operating condition. Consequently, the method could not be based on quantities that are not measured from the device or special conditions. We have chosen the equation which calculates the life expectancy of a ball bearing for the main failure mechanism, and developed an algorithm around it. The equation is workable since its variables are values known through measurements and properties of the fan or the bearing, which can be discovered from the component manufacturer.

Furthermore, we have introduced the program, implemented by the author as a practical part of this work. At the moment, the control of a fan's lifetime in the frequency converter's software is performed by a simple counter. The counter starts to run at the beginning of the fan's usage, and when it reaches user-defined time limit, the software gives the user a warning to replace the fan. The program developed in this work is a step towards more prognostic control of a fan's lifetime: its purpose is to evaluate a fan's life expectancy according to the real loading experienced by the fan.

We have presented the calculation method and the structure of the program. Input variables of the program are quantities possessing information of the prevailing state of loading, specifically the rotation speed of the fan and the bearing temperature, and properties of the fan or the bearing influencing the fan's lifetime. The program observes values of the changing input quantities measured from the device, calculates the life expectancy according to them, and moreover, adjusts the value of life expectancy according to the loading history. As output quantities the program provides that adjusted value of life expectancy, its derivative, the expectancy of the remaining life and the largest temperature experienced by the bearing. A version of the program was implemented with Codesys software. As a result, ABB has expressed their interest for implementing the program to their software interface for the devices that are sold to customers.

Lastly we have discussed the limitations and the future of the program. We have stated there are factors influencing a fan's lifetime that the program does not take into account. In the further study, more sophisticated algorithm could be developed. Methods for considering more environmental factors, such as humidity, vibration and dust could be search for. In addition, a more accurate temperature model for determining the bearing temperature could be compiled. Moreover, it could be examined, how a fan's non-operating condition and processes of turning the fan on and off, influence its lifetime.

6 References

Aarniovuori, L., Laurila, L., Niemelä, M. and Pyrhönen, J., 2007. Loss Calculation of a Frequency Converter with a Fixed-step Circuit Simulator. In: *Power Electronics and Applications*. Aalborg 2-5 Sept. 2007. p. 1-9.

ABB Oy, 2012. *Hardware Manual, ACS880-01 drives, 3AUA0000078093 Rev E*. [pdf] ABB Oy. Available at: <http://search-ext.abb.com/library/Download.aspx?DocumentID=3AUA0000078093&LanguageCode=en&DocumentPartId=1&Action=Launch> [Accessed 5 September 2012].

Azar, K., Engelberts N., Goodman C., Haskell M., Pourvash M. and Tavasolli B., 2008. *Qpedia, Thermal eMagazine, Volume 1, Issues 1-12*. Massachusetts: Advanced Thermal Solutions, Inc. ISBN 0-615-23660-5.

Blaabjerg, F., Jaeger, U. and Munk-Nielsen, S., 1995. Power Losses in PWM-VSI Inverter Using NPT or PT IGBT Devices. *IEEE Transactions on Power Electronics*, 10(3), p. 358-367.

Chitode, J.S., 2009. *Power Electronics*. 4th rev. ed. Pune: Technical Publications Pune. ISBN 8-18431638-4.

IPC, 2006. *IPC-9591 - Performance Parameters (Mechanical, Electrical, Environmental and Quality/Reliability) for Air Moving Devices*. Bannockburn, Illinois: IPC.

International Standards Office, 2007. *ISO 281 - Rolling Bearings -- Dynamic Load Ratings and Rating Life*. ISO.

Jin, X., Ma, E.W.M., Chow, T.W.S. and Pecht, M., 2012. An Investigation into Fan Reliability. In: *Prognostics and System Health Management (PHM)*. Beijing 23-25 May 2012. p. 1-6.

Kececioglu, D., 2002. *Reliability & Life Testing Handbook, Volume 2*. Lancaster, Pennsylvania: DEStech Publications, Inc. ISBN 1-932078-03-7.

Khonsari, M.M. and Booser E.R., 2008. *Applied Tribology: Bearing Design and Lubrication*. 2nd ed. West Sussex, England: John Wiley & Sons, Ltd. ISBN 0-470-05711-7.

Kyyrä, J., 2010. *Suuntaajatekniikka*. Otaniemi: Aalto-yliopiston teknillisen korkeakoulun sähkötekniikan laitos.

Lee, H., 2010. *Thermal Desing: Heat Sinks, Thermoelectrics, Heat Pipes, Compact Heat Exchangers and Solar Cells*. Hoboken, New Jersey: John Wiley & Sons, Inc. ISBN 0-470-49662-6.

Madsen, D.A., Dr. Folkestad, J., Schertz, K.A., Schumaker, T.M., Stark, C. and Turpin, J.L., 2004. *Engineering Drawing and Design.* 3rd ed. New York: Delmar, Thomson Learning. ISBN 0-7668-1534-6.

Martin, P.L., 1999. *Electronic Failure Analysis Handbook*. USA: The McGraw-Hill Companies, Inc. ISBN 0-07-041044-5.

Miao, Q., Azarian, M. and Pecht, M., 2011. Cooling Fan Bearing Fault Identification Using Vibration Measurement. In: *Prognostics and Health Management (PHM)*. Montreal, QC 20-23 June 2011. p. 1-5.

Misra, K.B. ed., 2008. *Handbook of Performability Engineering*. London: Springer-Verlag London Limited. ISBN 1-84-800-130-5.

Mohan, N., Undeland, T.M. and Robbins, W.P., 2003. *Power Electronics*. 3rd ed. Hoboken, New Jersey: John Wiley & Sons, Inc. ISBN 0-471-22693-9.

Niiranen, J., 2007. *Tehoelektroniikan komponentit*. 4th ed. Helsinki: Otatieto, Gaudeamus, Helsinki University Press. ISBN 978-951-672-317-7.

NSK, 2011. *Rolling Bearings, Cat. No. E1102j*. [pdf] NSK Ltd. Available at: <http://www.jp.nsk.com/app01/en/ctrg/index.cgi?inpGroup=bearings> [Accessed 5 September 2012].

NSK, 2013. *Introduction to Bearings*. [online] Available at: <http://www.nsk.com/services/basicknowledge/introduction.html> [Accessed 7 January 2013].

NSK Americas a. *False brinelling*. [online] Available at: <http://www.nskamericas.com/cps/rde/xchg/na_en/hs.xsl/false-brinelling.html> [Accessed 15 March 2013].

NSK Americas b. *Seizure*. [online] Available at: <http://www.nskamericas.com/cps/rde/xchg/na_en/hs.xsl/seizure.html> [Accessed 15 March 2013].

NSK representative, 2012. *Discussion on the bearing life equation*. [email] (Personal communication, 8 November 2012).

Oh, H., Azarian, M.H., Pecht, M., White, C.H., Sohaney, R.C. and Rhem, E., 2010. Physics-of-failure Approach for Fan PHM in Electronics Applications. In: *Prognostics and Health Management Conference*. Macao 12-14 Jan 2010. p 1-6.

Ohring, M., 1998. *Reliability and Failure of Electronic Materials and Devices*. San Diego: Academic Press. ISBN 0-12-524985-3.

Orlov P., 1977. *Fundamentals of Machine Design, Part 4*. Translated from Russian by. A. Troitsky. Moscow: Mir Publishers.

Phakatkar, H.G. and Ghorpade, R.R., 2009. *Tribology*. 2nd ed. Shivaji Nagar: Nirali Prakashan.

Ramana, B.V., 2007. *Higher Engineering Mathematics*. New Delhi: Tata McGraw-Hill Publishing Company Ltd. ISBN 0-07-063419-0.

Sahoo, P., 2005. *Engineering tribology*. New Delhi: Prentice-Hall of India. ISBN 81-203-2724-1.

Servo, 2009. *AC/DC Axial Fans & Blowers, Technical Data*. [pdf] Servo. Available at: <http://www.nidec-servo.com/en/digital/pdf/g_fab_technical.pdf> [Accessed 5 September 2012].

Sharma C.S. and Purohit K., 2005. *Desing of Machine Elements*. New Delhi: Prentice-Hall of India Private Ltd. ISBN 81-203-1955-9.

Sidharth, S., Sundaram, S., 2004. A Methodology to Assess Microprocessor Fan Reliability. In: *Thermal and Thermomechanical Phenomena in Electronic Systems*. Sunnyvale, CA 1-4 June 2004. p. 96-101.

Sousa, G.C.D., Bose, B.K., Cleland, J., Spiegel, R.J. and Chappell, P.J., 1992. Loss Modeling of Converter Induction Machine System for Variable Speed Drive. In: *Industrial Electronics, Control, Instrumentation, and Automation*. San Diego, CA 9-13 Nov 1992. p. 114-120.

Sundquist H.,1986. *Tribologian perusteet*. Otaniemi: Otakustantamo. ISBN 951-671-377-7.

Tian, X., 2006. Cooling Fan Reliability: Failure Criteria, Accelerated Life Testing, Modeling and Qualification. In: *Reliability and Maintainability Symposium*. Newport Beach, CA 23-26 Jan 2006. p. 380-384.

Tong, X.C., 2011. *Advanced Materials for Thermal Management of Electronic Packaging*. New York: Springer Science + Business Media. ISBN 1-4419-7758-8.

Yang, G., 2007. *Life Cycle Reliability Engineering*. Hoboken, New Jersey: John Wiley & Sons, Inc. ISBN 0-471-71529-8.